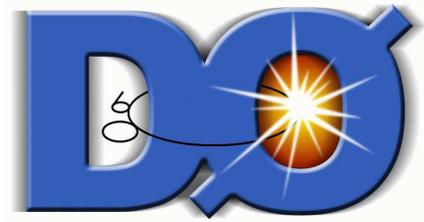


# Search for Supersymmetry at DØ

Volker Büscher

Universität Freiburg



Wine & Cheese Seminar, Fermilab, May 20 2005

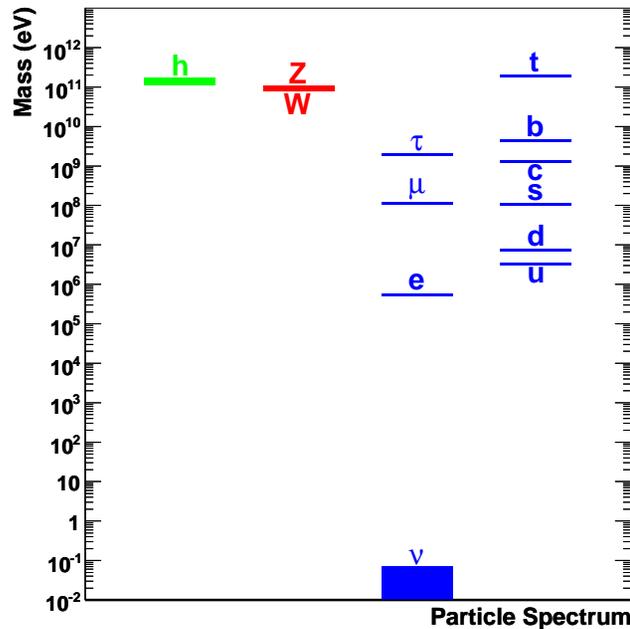
- **Introduction**
- **Squarks and Gluinos**
- **Charginos and Neutralinos**
  - **Trileptons**
  - **SUSY with R-parity violation**
  - **Stable Charginos**
  - **Gauge-Mediated SUSY Breaking**
- **$B_s \rightarrow \mu^+ \mu^-$ , SUSY Higgs bosons**

# The Standard Model and beyond

The Standard Model is incomplete: gravitation, dark matter...

The Standard Model has many free parameters:

Masses



Mixing Matrices

Mass eigenstates  $\rightarrow$  Gauge eigenstates

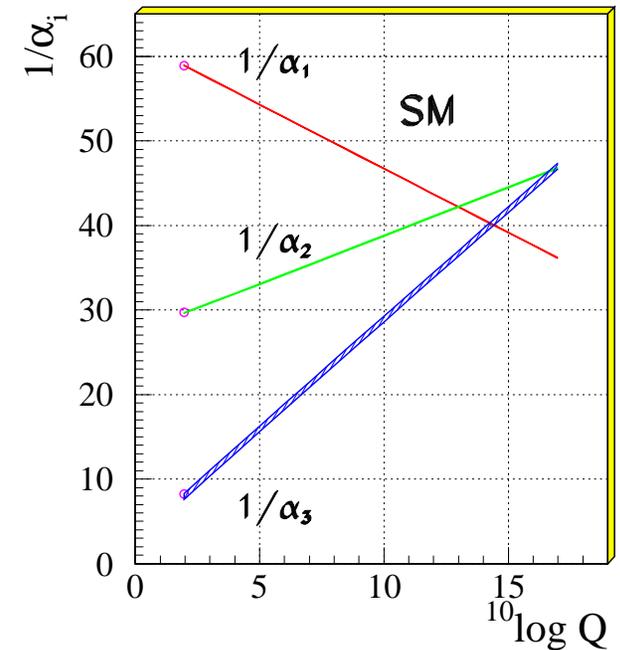
Quarks

$$\begin{pmatrix} \mathbf{1} & 0.2 & 0.005 \\ 0.2 & \mathbf{1} & 0.04 \\ 0.005 & 0.04 & \mathbf{1} \end{pmatrix}$$

Neutrinos

$$\begin{pmatrix} \mathbf{0.8} & \mathbf{0.5} & \approx 0 \\ \mathbf{0.4} & \mathbf{0.6} & \mathbf{0.7} \\ \mathbf{0.4} & \mathbf{0.6} & \mathbf{0.7} \end{pmatrix}$$

Gauge couplings

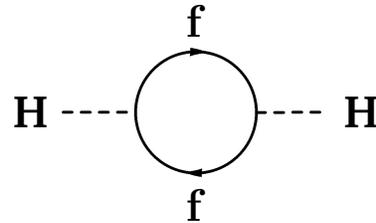


$\rightarrow$  there must be a more fundamental and complete theory

# The Standard Model and beyond

## Strong hint: The hierarchy problem

- fermion loop corrections to Higgs mass are divergent
- Higgs mass should be of the order of the cutoff scale (e.g.  $M_{\text{Planck}}$ )

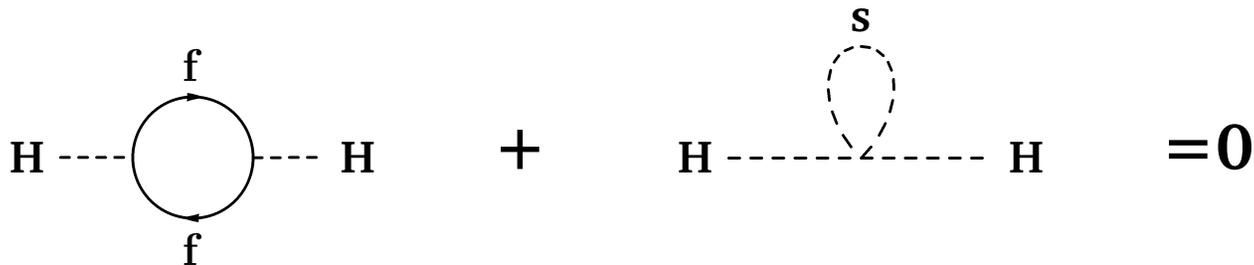


- in contradiction to indirect evidence for a light SM Higgs boson
- there must be something beyond the SM that modifies these corrections

## Two main options:

1. New physics at  $O(1 \text{ TeV})$  → loop corrections stay “reasonably” small
2. New symmetry that suppresses loop corrections

Most straightforward way: cancel fermion loops with boson loops



# Supersymmetry

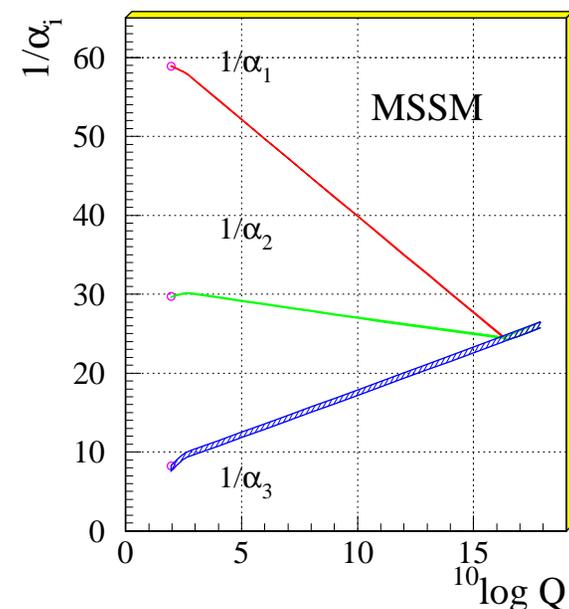
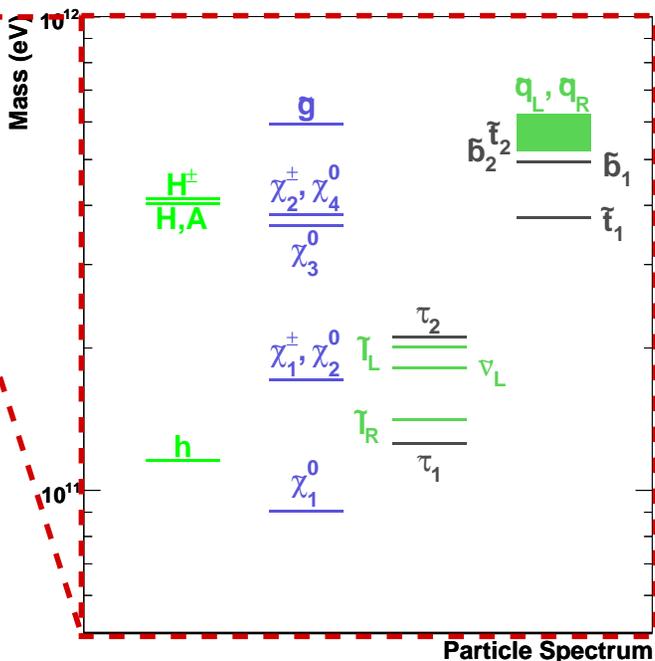
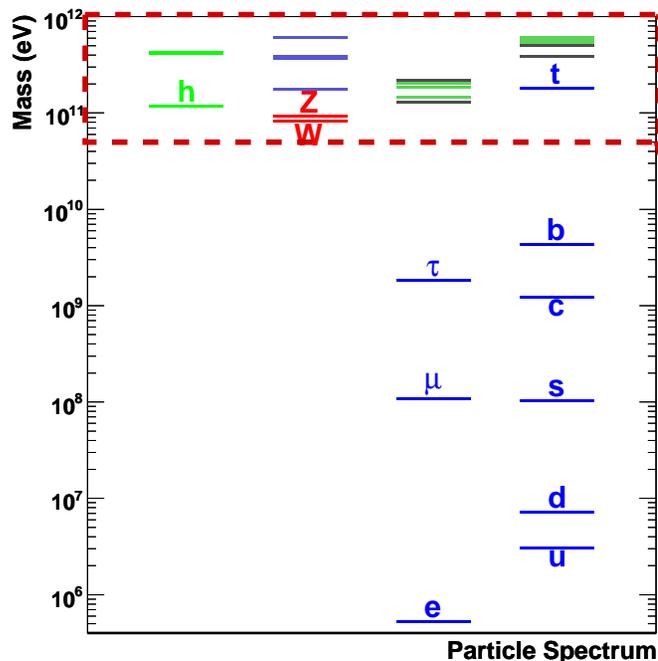
The idea: particle physics is symmetric under transformation fermion  $\leftrightarrow$  boson

→ implies one supersymmetric partner for each SM particle

Superpartners are heavy → SUSY must be broken

– Details of SUSY breaking mechanism unknown

→ need to consider several models: gravity-, gauge-, anomaly-mediated breaking



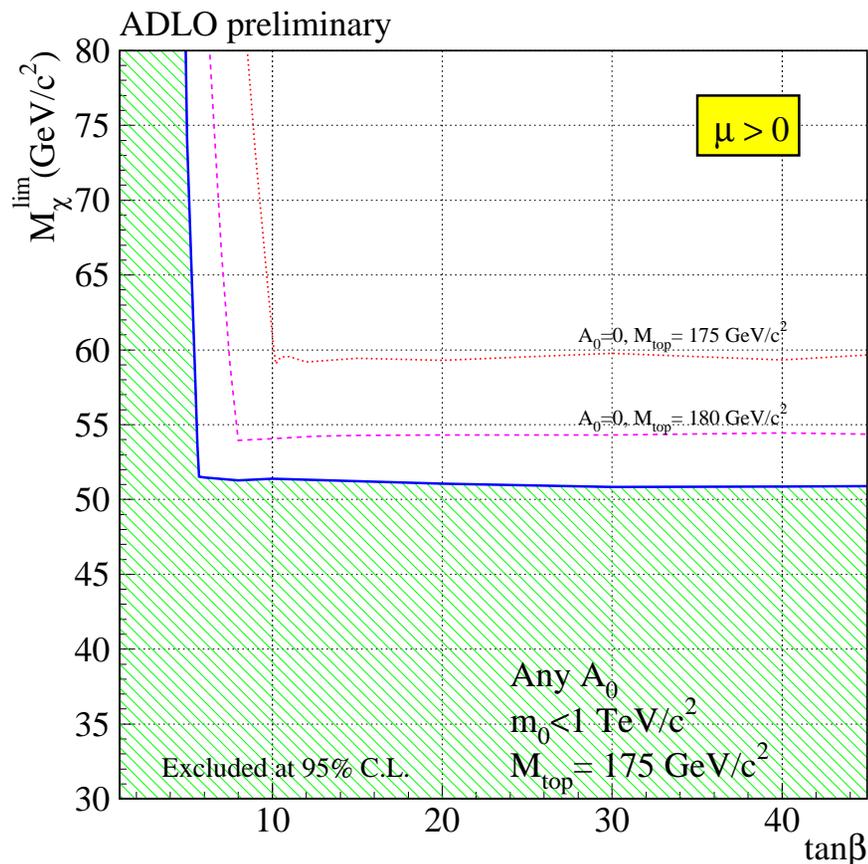
Additional benefits of SUSY:

- provides potential dark matter candidate
- predicts gauge unification → Grand Unified Theories
- local supersymmetry → quantum gravity

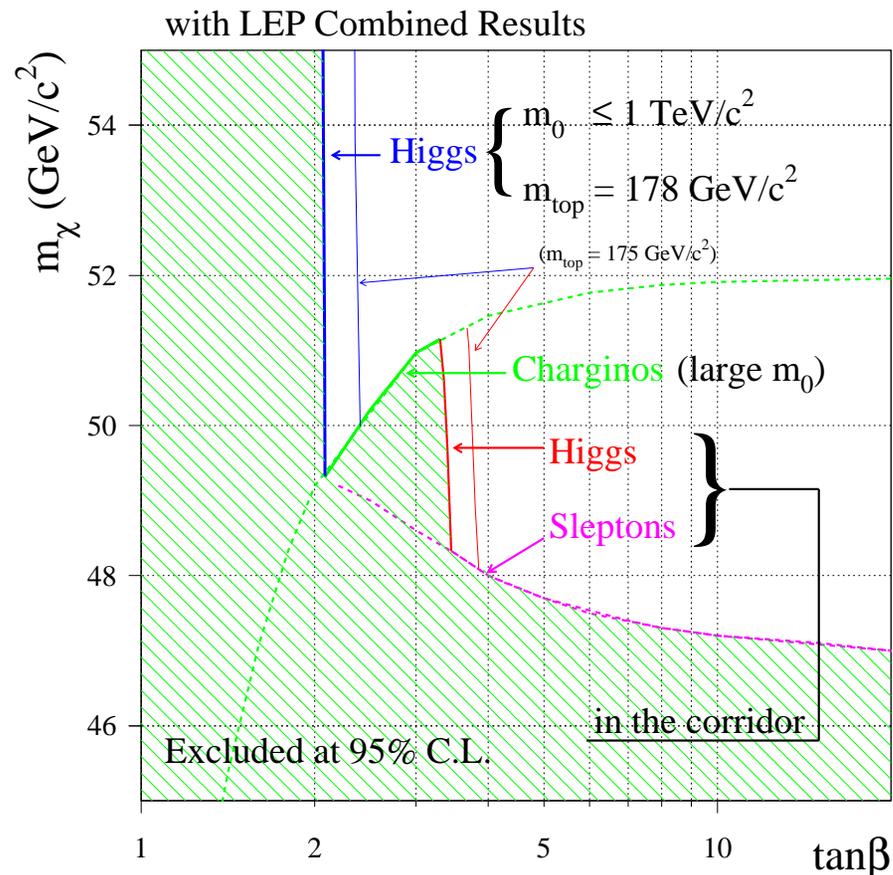
# Search for Supersymmetry at LEP

- Very clean environment, highly efficient searches for large variety of signatures
- Main limitation: maximum beam energy of  $\approx 104$  GeV
- Strong limits on SUSY from searches for charginos, sleptons and Higgs bosons:
 
$$m_{\tilde{\chi}^\pm} > 103.5 \text{ GeV}, m_{\tilde{\ell}} \gtrsim 95 \text{ GeV}, m_h > 114.4 \text{ GeV}$$
- Within a given model, can derive mass limits on LSP (dark matter candidate)

LSP Mass Limit in mSUGRA



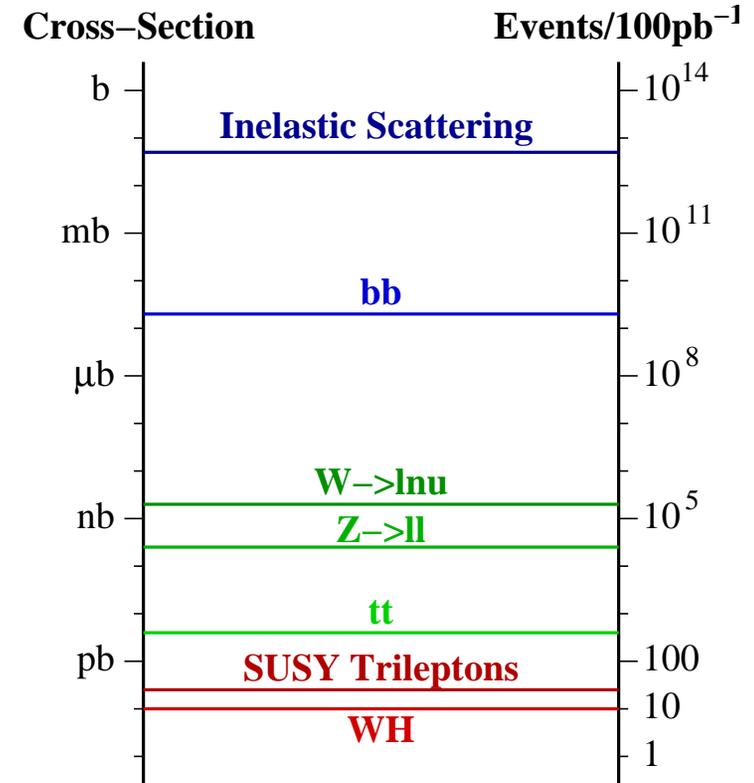
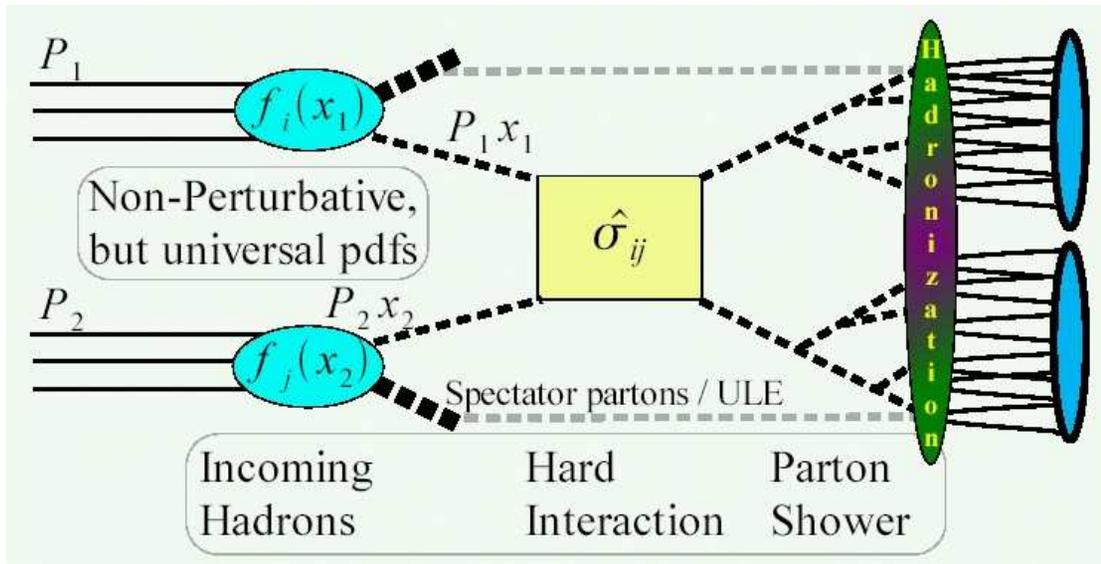
LSP Mass Limit in MSSM



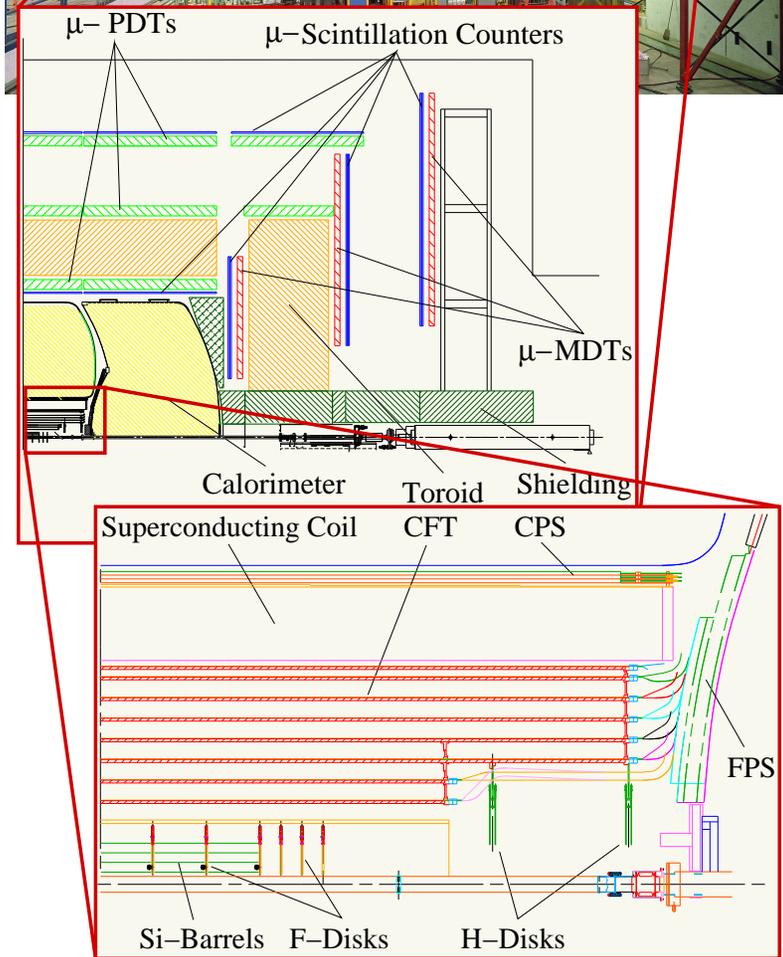
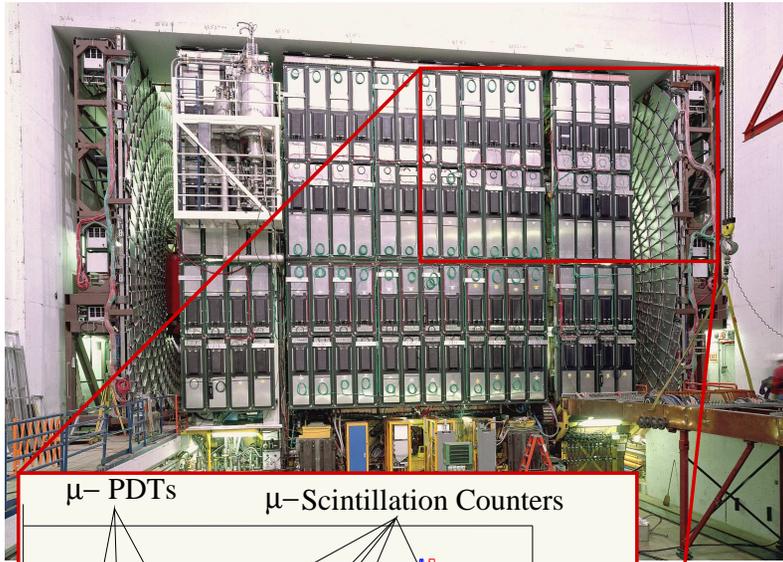
# Physics at the Tevatron

Tevatron: Proton-Antiproton Collider at  $\sqrt{s}=1.96$  TeV, collisions every 396 ns

- Advantage: High centre-of-mass energy
  - production of massive particles (LEP:  $m \lesssim 100$  GeV)
- Disadvantage: Strong Interaction
  - huge event rates for jet production
  - complicated final states:
    - particles from fragmentation of  $p/\bar{p}$  remnants
    - gluon radiation → jets



# The DØ Detector



Excellent Coverage for  $e, \mu, \tau, E_T, b$ -tagging:

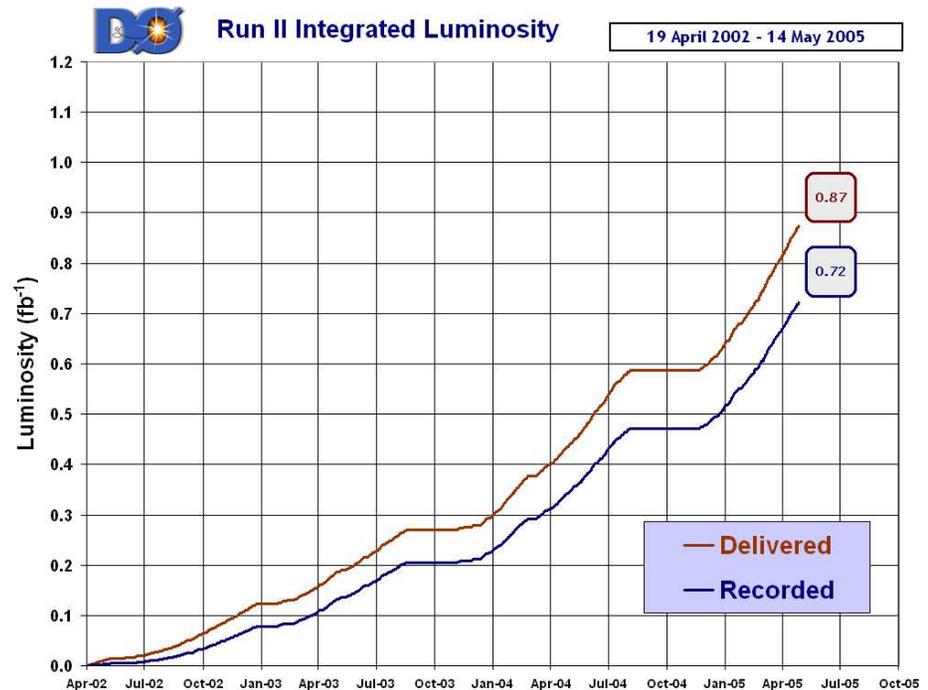
Electron acceptance	$ \eta  < 3.0$
Muon acceptance	$ \eta  < 2.0$
Silicon Precision tracking	$ \eta  < 3.0$
LAr Calorimeter	$ \eta  < 4.2$

Powerful trigger systems (2.5 MHz  $\rightarrow$  50 Hz)

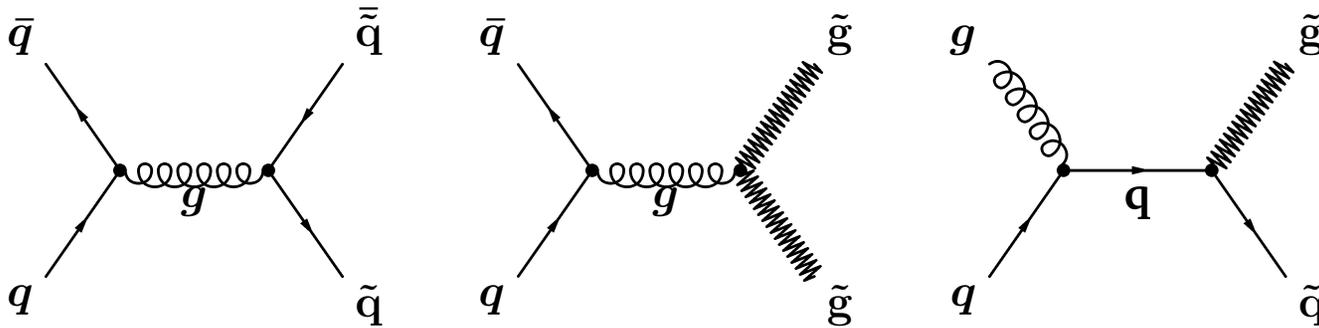
- Dilepton triggers starting at  $p_T > 4$  GeV
- Jets +  $E_T$  triggers with  $E_T > 25$  GeV

More than  $0.7 \text{ fb}^{-1}$  collected so far

- Current Average Efficiency  $\approx 90\%$

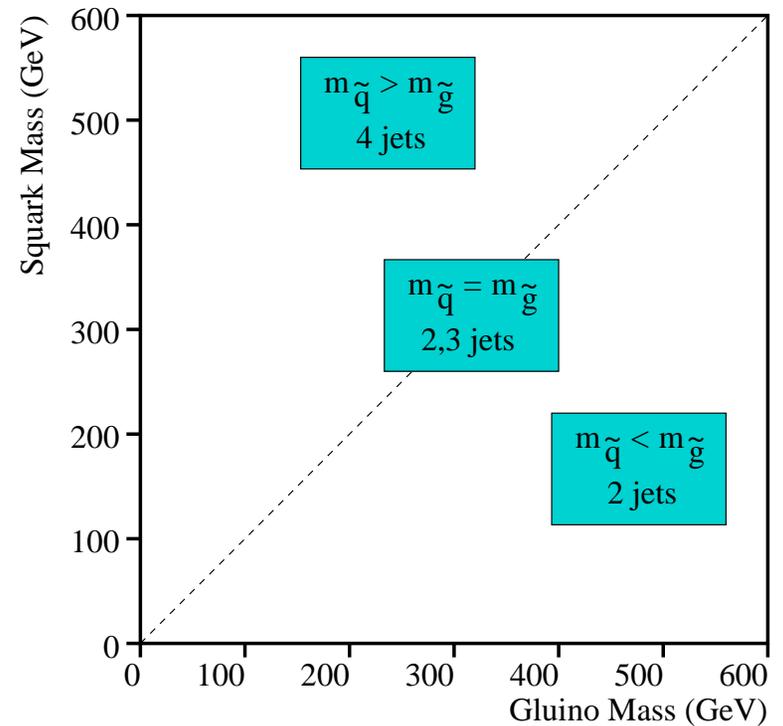


# Search for Supersymmetry – Squarks/Gluinos



- Squarks/Gluinos produced via strong interaction
  - large cross sections at hadron colliders
- Decays: jets + LSP
  - LSP assumed to be stable ( $R_p$  conserved)
  - Signature: jets +  $E_T$
- $310 \text{ pb}^{-1}$  collected with dedicated trigger:
  - acoplanar jets +  $E_T$

Mass region	Main Channel	Signature
$m_{\tilde{q}} < m_{\tilde{g}}$	$\tilde{q}\tilde{q}$	$2j + E_T$
$m_{\tilde{q}} > m_{\tilde{g}}$	$\tilde{g}\tilde{g}$	$4j + E_T$
$m_{\tilde{q}} \approx m_{\tilde{g}}$	$\tilde{q}\tilde{q}, \tilde{q}\tilde{g}$	$2j/3j + E_T$

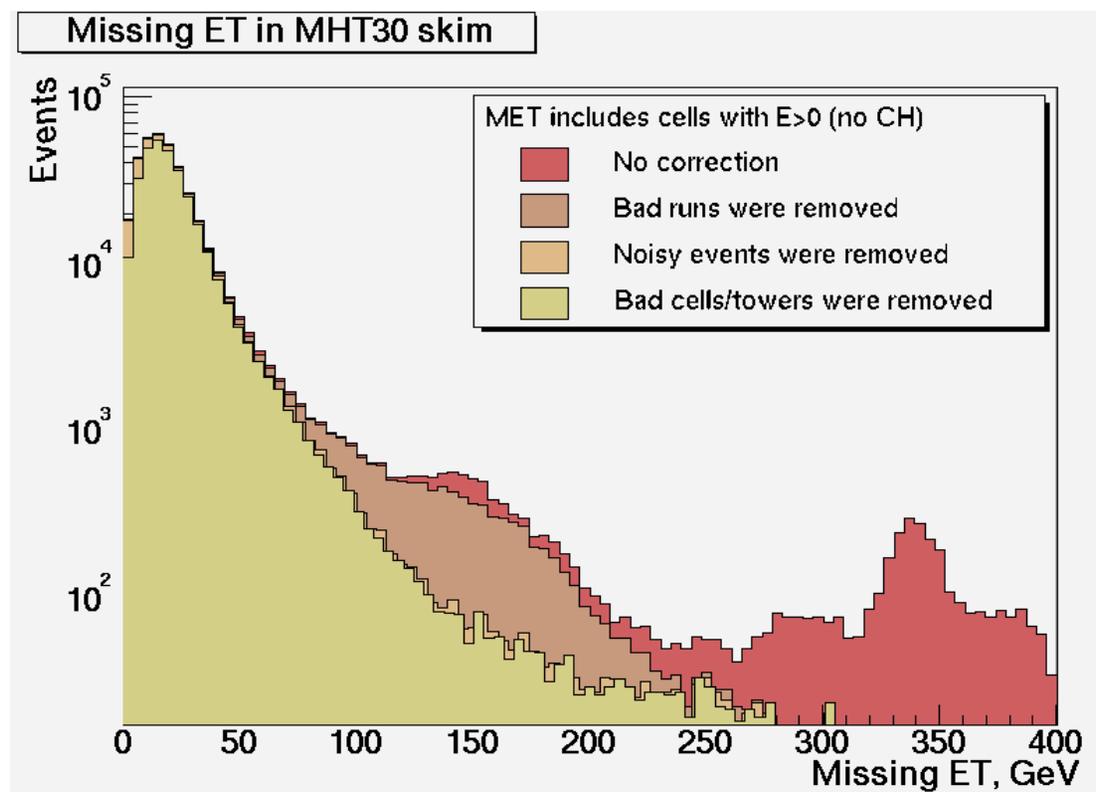


# Search for Supersymmetry – Squarks/Gluinos

Searching for one SUSY event with high  $E_T$  out of  $10^{14}$   $p\bar{p}$  collisions

→ very sensitive to rare calorimeter problems

Missing  $E_T$  distribution (before quality cuts)



Deployed extensive data quality monitoring effort

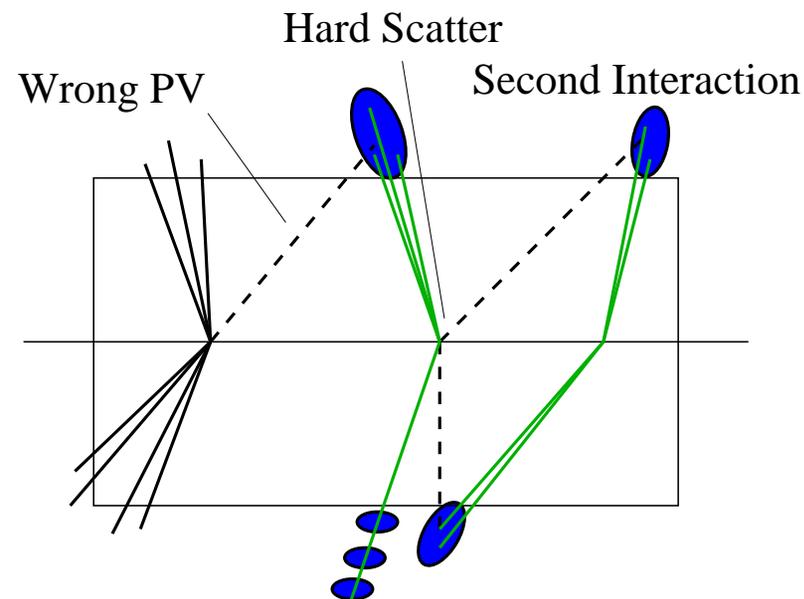
→ offline tools to veto bad blocks of data

→ early online detection and fixing of detector problems

# Search for Supersymmetry – Squarks/Gluinos

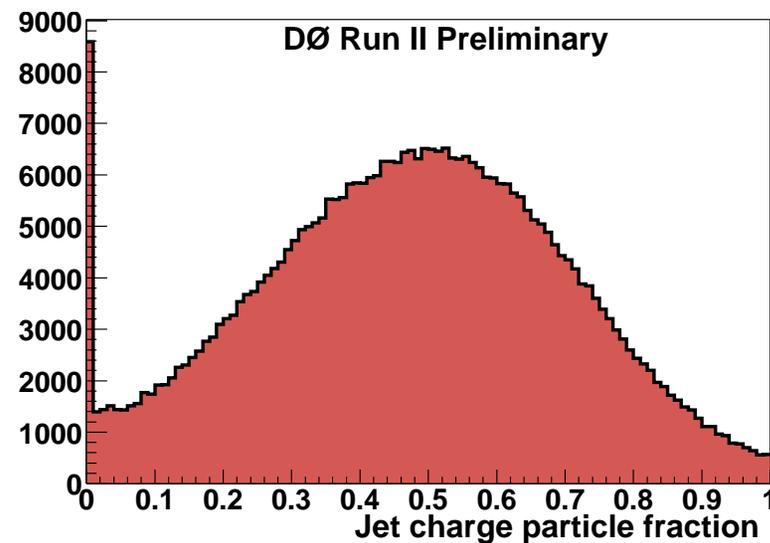
Fake  $E_T$  can be caused by:

- wrong primary vertex
- energy from additional interactions
- showers generated by cosmic muons
- calorimeter noise
- beam background



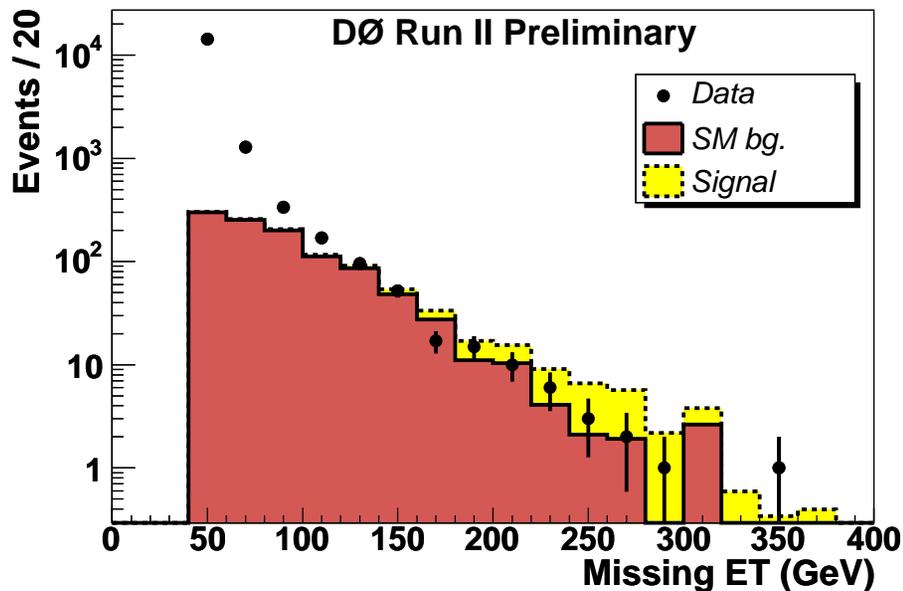
**Solution:**

- sum transverse momenta of charged particles pointing from primary vertex to jet energy deposition in calorimeter
- require a minimum charged particle fraction for each jet

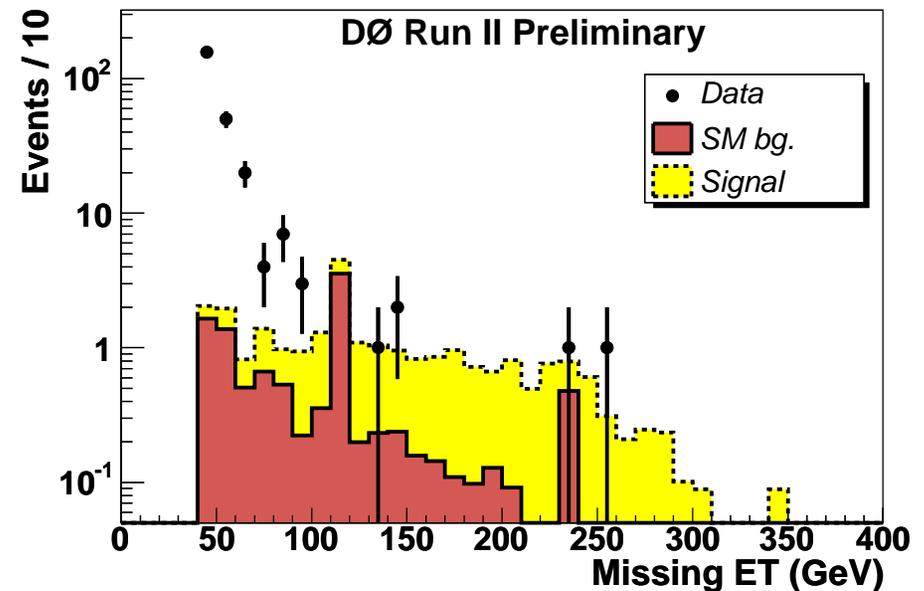


# Search for Supersymmetry – Squarks/Gluinos

Preselection Stage



3-Jets Analysis before final cut



## Main backgrounds:

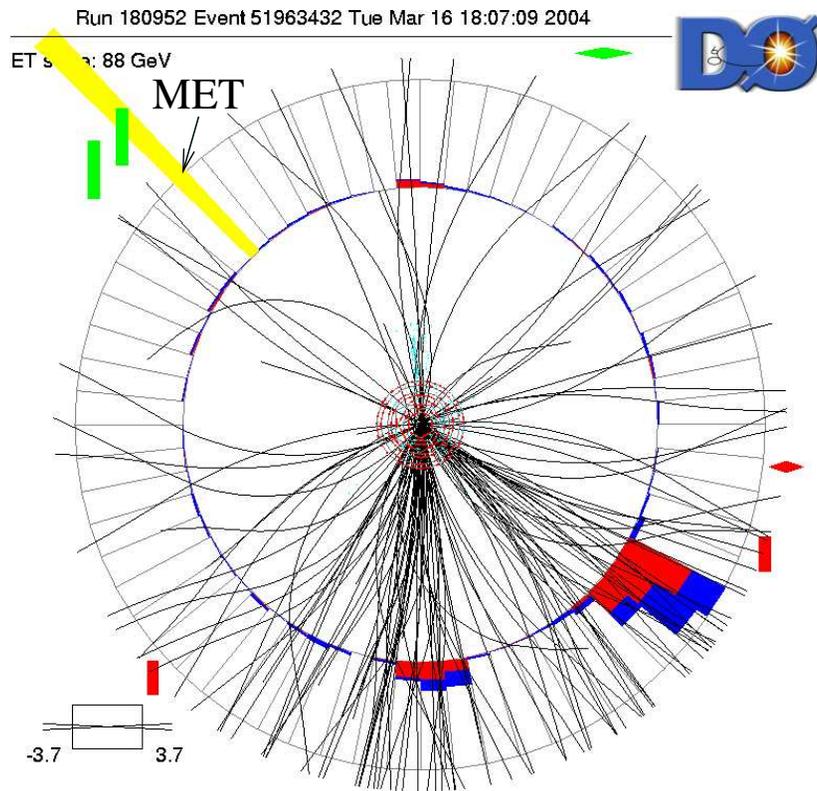
- Multijets with fake  $E_T$
- W+jets with  $W \rightarrow e\nu, \mu\nu, \tau\nu$
- Z+jets with  $Z \rightarrow \nu\bar{\nu}$

## Main selection cuts:

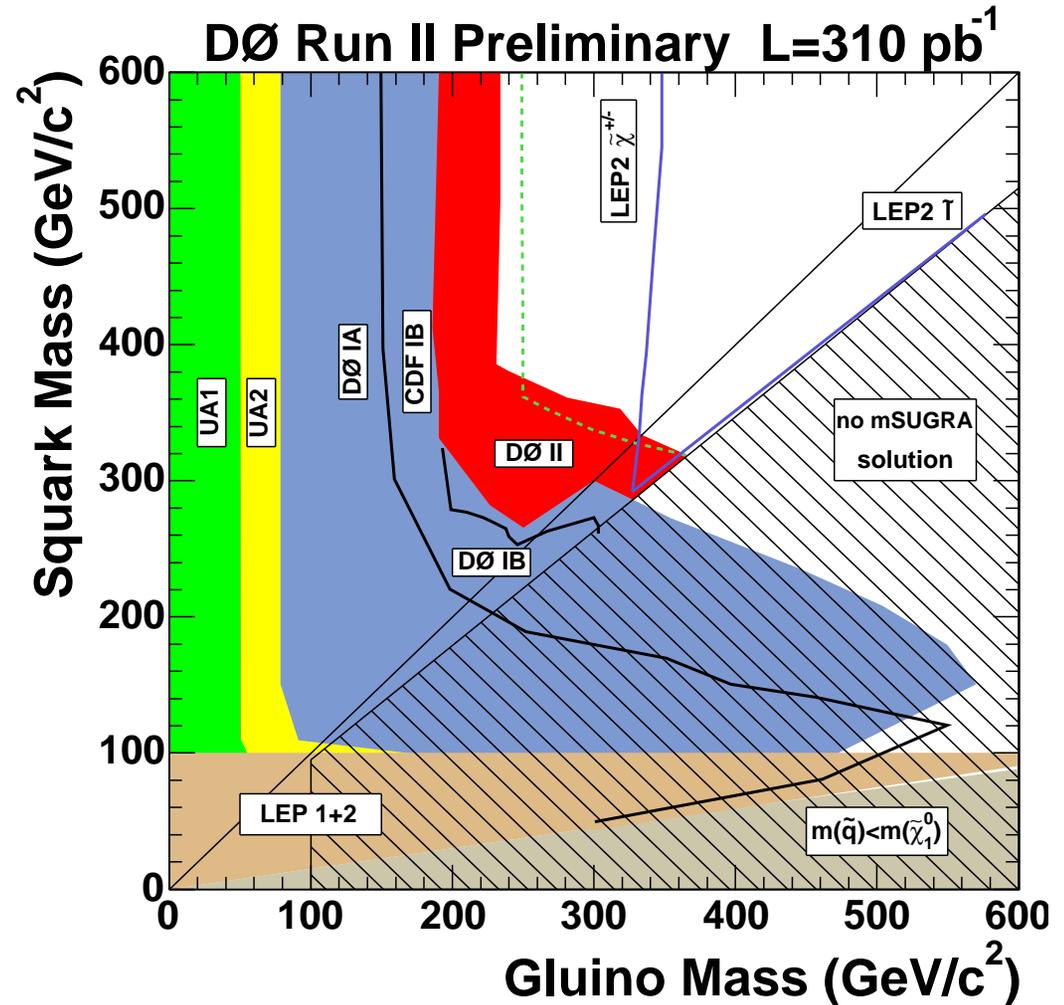
- 2/3/4 jets and large  $E_T$
- separation of  $E_T$  direction and jets
- veto events with isolated leptons

Mass region	Main Channel	Signature	$E_T$	$H_T = \sum p_T^{jet}$	Exp. Bckgd.	Data
$m_{\tilde{q}} < m_{\tilde{g}}$	$\tilde{q}\tilde{q}$	2j + $E_T$	>175 GeV	>250 GeV	$12.8 \pm 5.4$	12
$m_{\tilde{q}} > m_{\tilde{g}}$	$\tilde{g}\tilde{g}$	4j + $E_T$	>75 GeV	>250 GeV	$7.1 \pm 0.9$	10
$m_{\tilde{q}} \approx m_{\tilde{g}}$	$\tilde{q}\tilde{q}, \tilde{q}\tilde{g}$	2j/3j + $E_T$	>100 GeV	>325 GeV	$6.1 \pm 3.1$	5

# Search for Supersymmetry – Squarks/Gluinos

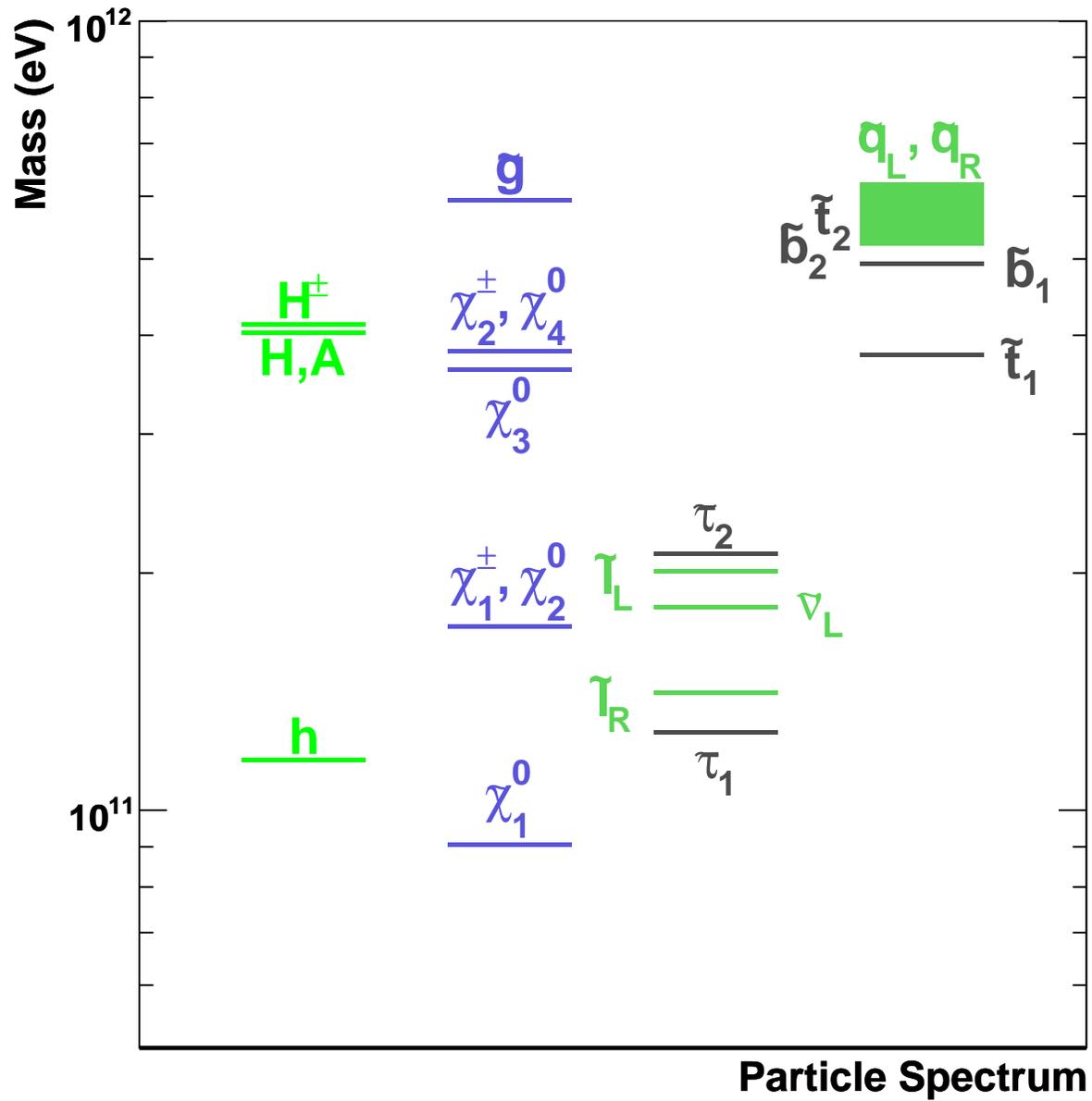


$\tilde{q}\tilde{q}$  candidate event  
 ( $E_T = 380$  GeV,  $p_T^{j1} = 290$  GeV,  $p_T^{j2} = 120$  GeV)



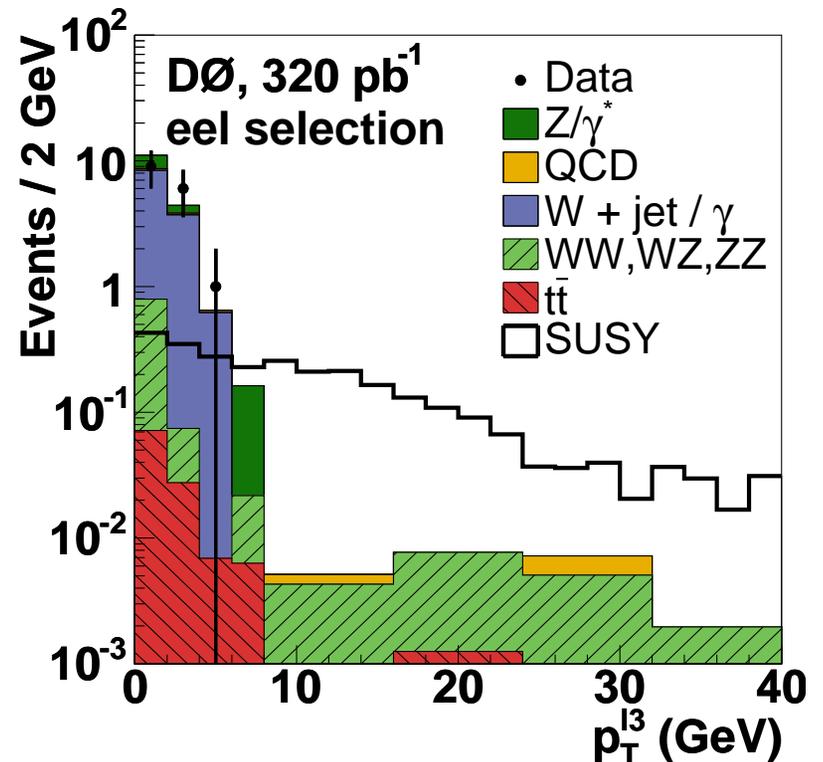
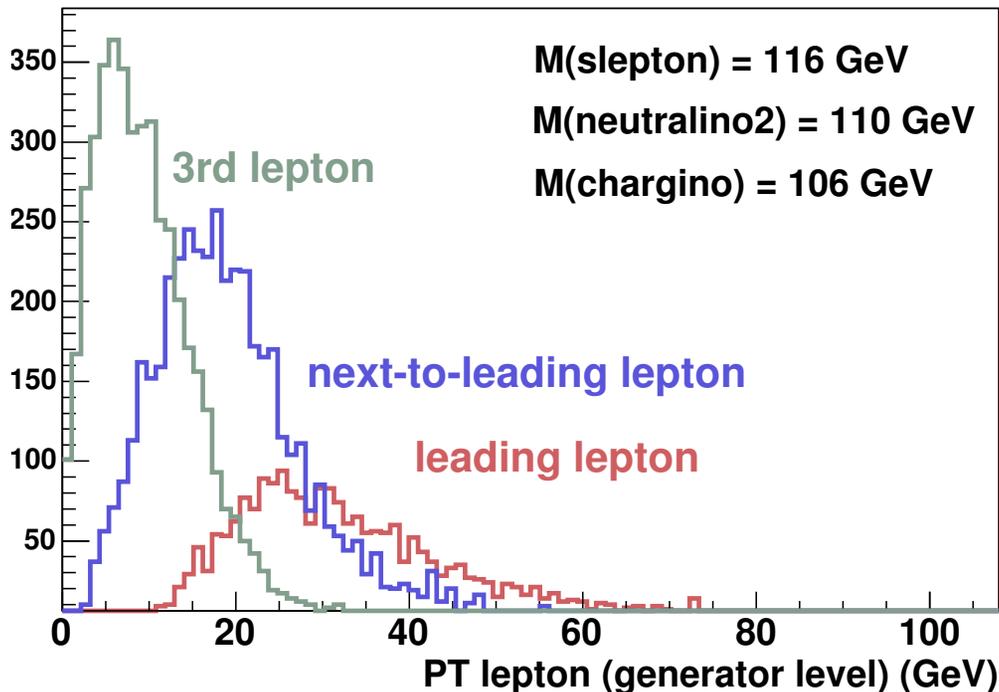
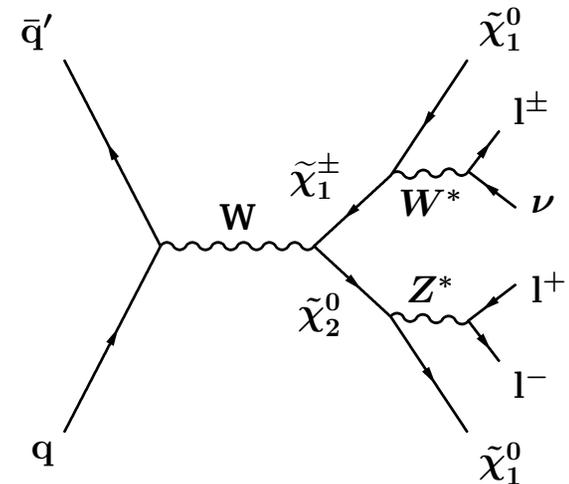
- No evidence for squark/gluino production at the Tevatron
- New limits in squark/gluino mass plane (mSUGRA:  $\tan\beta = 3$ ,  $A_0 = 0$ ,  $\mu < 0$ )
  - neglecting contributions from stop production
  - more model-independent interpretation in progress (under discussion in TEVNPWG)
- Have reached sensitivity beyond Run I and LEP limits

# Typical mass spectrum of SUSY particles

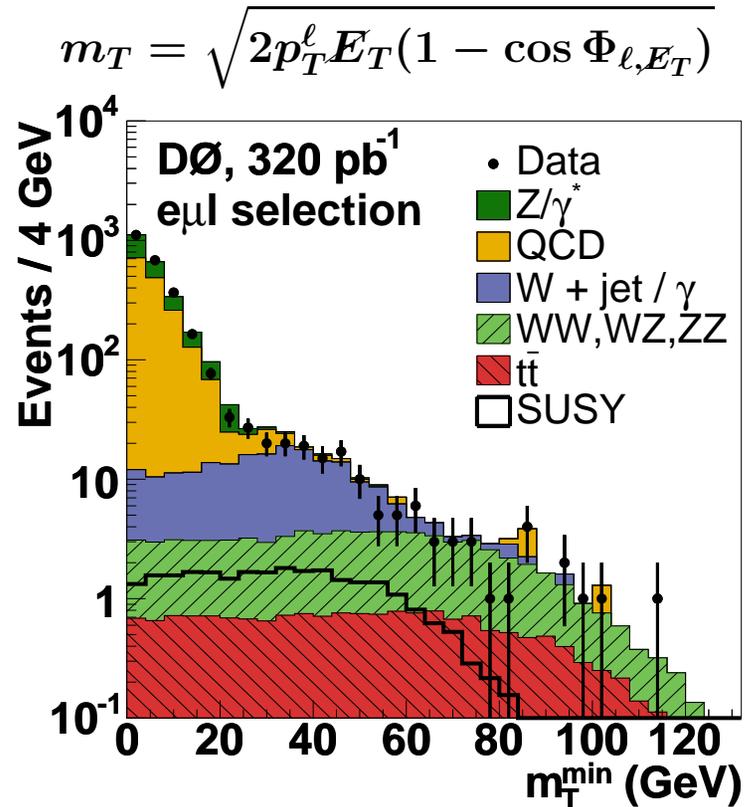
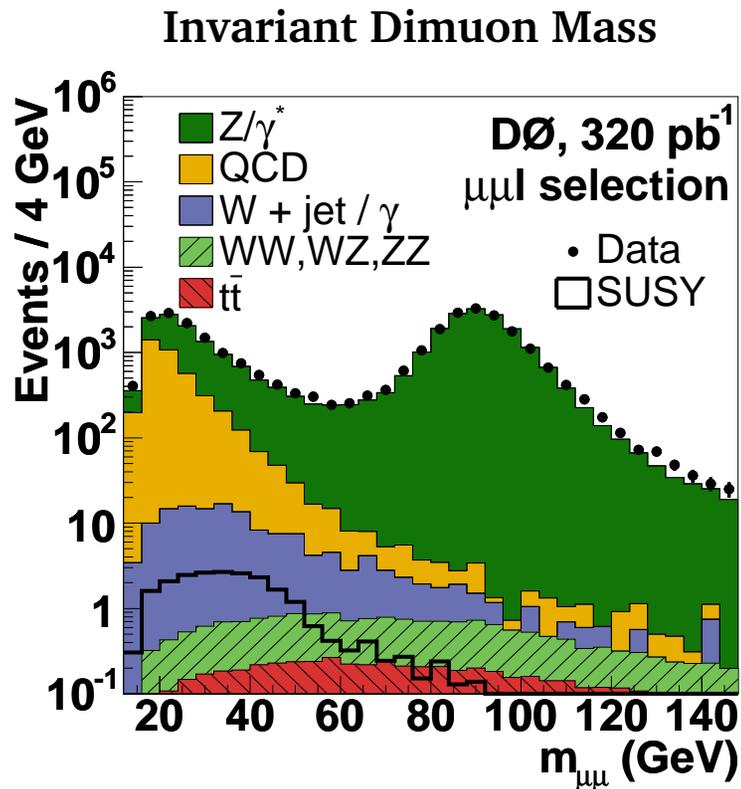


# Search for Charginos and Neutralinos

- Production cross section (electroweak) relatively small
  - need clean leptonic signature to suppress backgrounds
- Golden channel:  $\tilde{\chi}^{\pm} \tilde{\chi}_2^0 \rightarrow 3\ell + E_T$
- Experimental Challenge: low- $p_T$  leptons
  - need multilepton triggers with low thresholds
  - need efficient lepton identification at low  $p_T$
- Analysis Strategy:
  - two identified leptons plus isolated track ( $e, \mu, \tau$ )



# Search for Charginos and Neutralinos



## Backgrounds:

- Multijets with fake leptons
- Drell-Yan, Z-production with  $Z \rightarrow ll$
- WW, WZ, ZZ production

## Main selection cuts:

- Three leptons ( $ll$ +track)
- Missing transverse Energy
- veto events containing  $Z \rightarrow ll$  decays

Selection	$p_T^{\ell 1}$	$p_T^{\ell 2}$	$p_T^{\ell 3}$
$eel$	> 12 GeV	> 8 GeV	> 4 GeV
$e\mu\ell$	> 12 GeV	> 8 GeV	> 7 GeV
$\mu\mu\ell$	> 11 GeV	> 5 GeV	> 3 GeV
ls- $\mu\mu$	> 11 GeV	> 5 GeV	-

# Search for Charginos and Neutralinos

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Results (320 pb<sup>-1</sup>):

Selection	Expected Background	Observed	Signal ( $m_{\tilde{\chi}^\pm} = 110$ GeV)
$e e \ell$	$0.21 \pm 0.12$	0	$1.9 \pm 0.2$
$e \mu \ell$	$0.31 \pm 0.13$	0	$1.6 \pm 0.1$
$\mu \mu \ell$	$1.75 \pm 0.57$	2	$1.3 \pm 0.2$
ls- $\mu \mu$	$0.66 \pm 0.37$	1	$0.7 \pm 0.1$
Combined	$2.93 \pm 0.79$	3	$5.5 \pm 0.3$

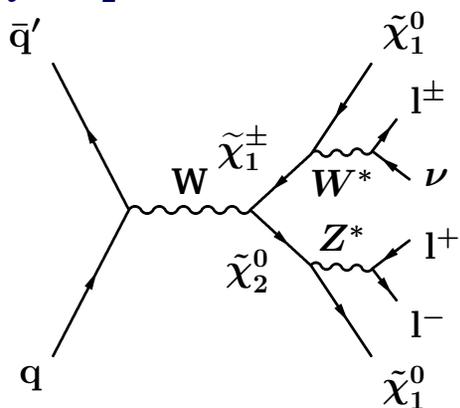
– Backgrounds dominated by WZ, WW, W $\gamma$  (plus  $b\bar{b}$  for dimuon channels)

→ No evidence for chargino/neutralino production

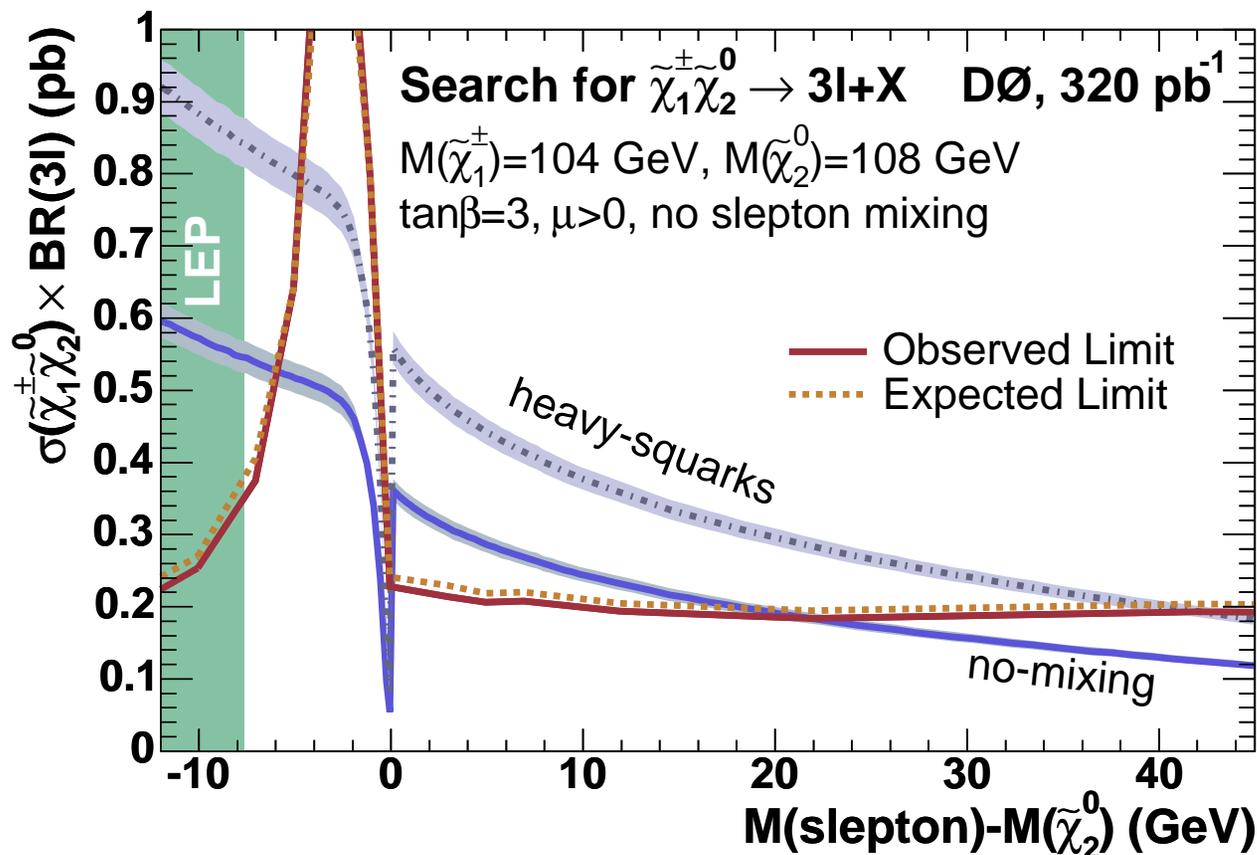
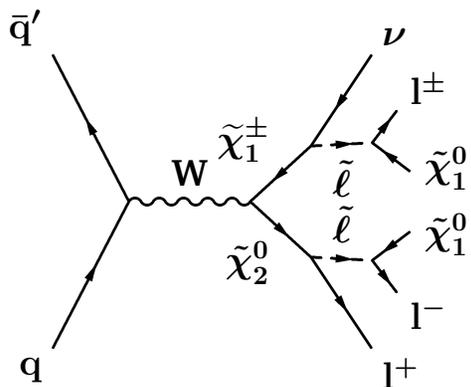
→ New limits on product of cross section and leptonic branching fraction

# Search for Charginos and Neutralinos

Heavy sleptons:



Light sleptons:



$\Delta M < 0$ : two-body decays into real sleptons

$\Delta M < -6 \text{ GeV}$ : good efficiency, high branching fractions

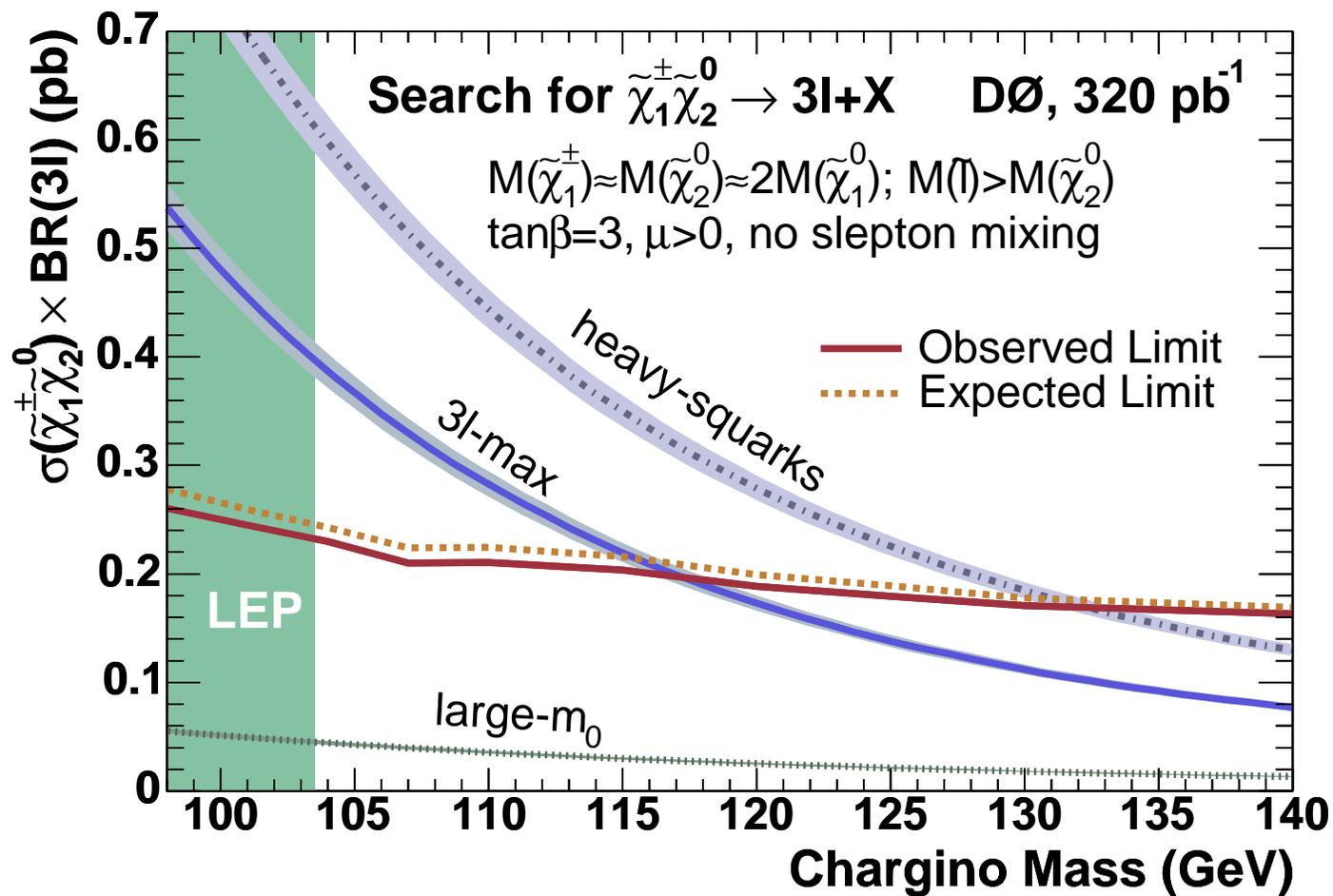
$-6 \text{ GeV} < \Delta M < 0$ : very soft third lepton  $\rightarrow$  limit set by  $ls-\mu\mu$ -analysis

$\Delta M > 0$ : three-body decays via slepton- and W/Z-exchange

$\Delta M \gtrsim 0$ : slepton-exchange maximal  $\rightarrow$  large  $BR(3l)$ : “3l-max scenario”

$\Delta M \gg 0$ : W/Z-exchange dominates  $\rightarrow$  small  $BR(3l)$ : “large- $m_0$  scenario”

# Search for Charginos and Neutralinos

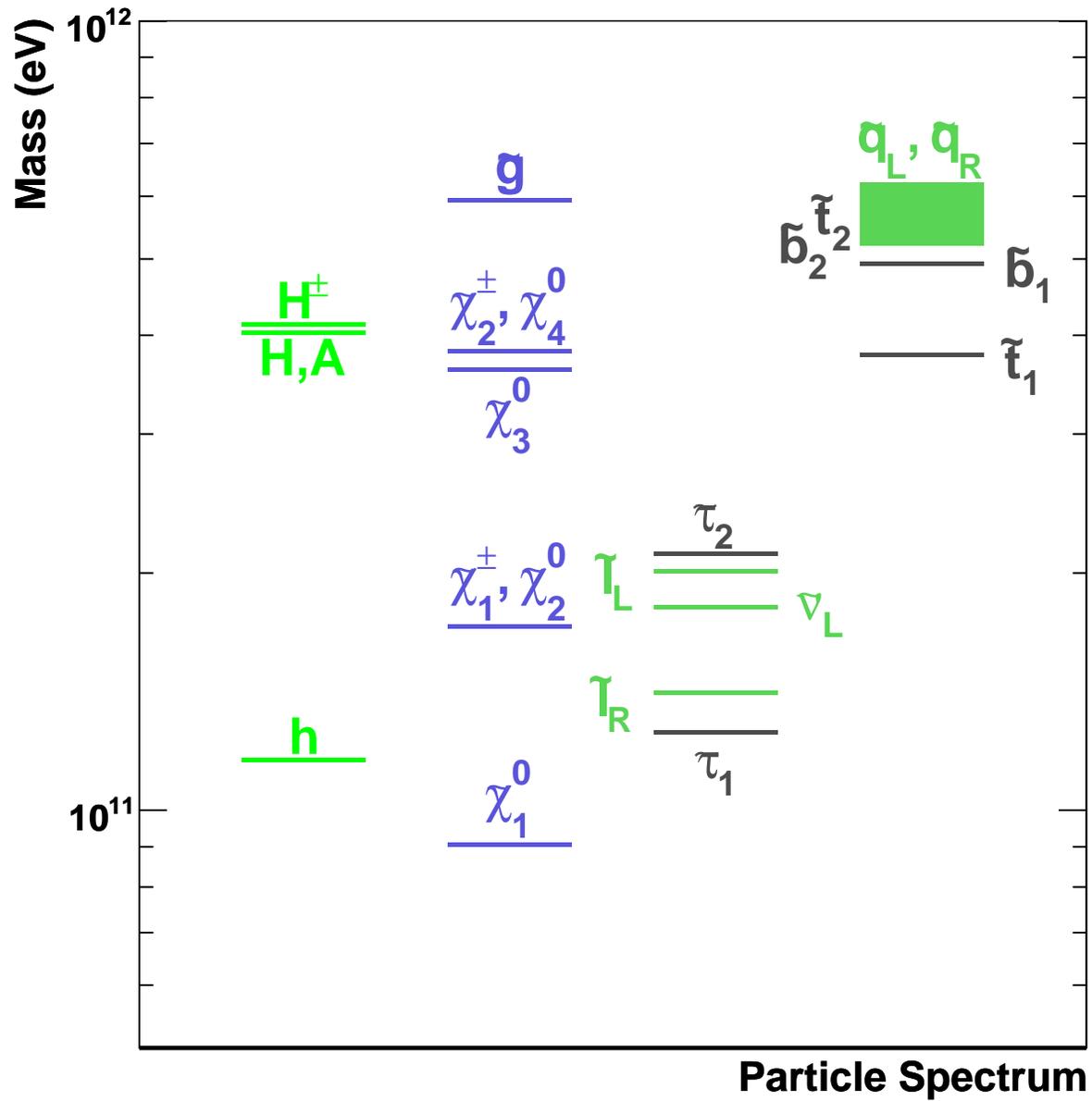


New limits constrain SUSY beyond LEP chargino limits

- 3l-max scenario:  $m_{\tilde{\chi}^\pm} > 117 \text{ GeV}$
- heavy-squarks scenario:  $m_{\tilde{\chi}^\pm} > 132 \text{ GeV}$

Assumption: degenerate slepton masses  $\rightarrow$  equal branching fractions into  $e, \mu, \tau$

# Typical mass spectrum of SUSY particles



# Search for Charginos and Neutralinos

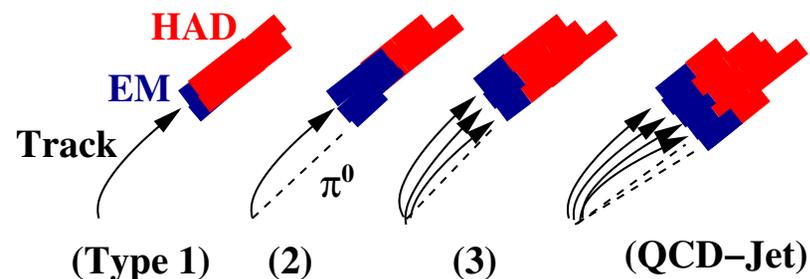
SUSY mass spectrum likely contains light stau leptons

→ chargino/neutralino decay cascades proceed via stau

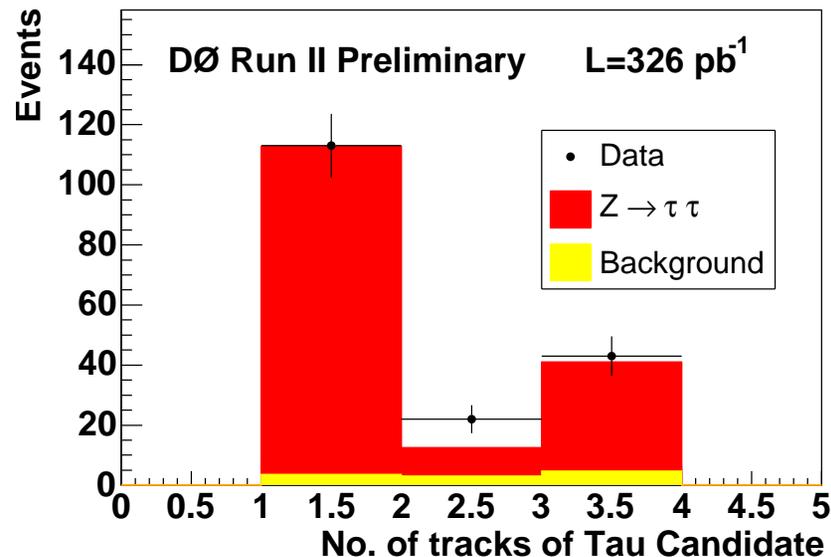
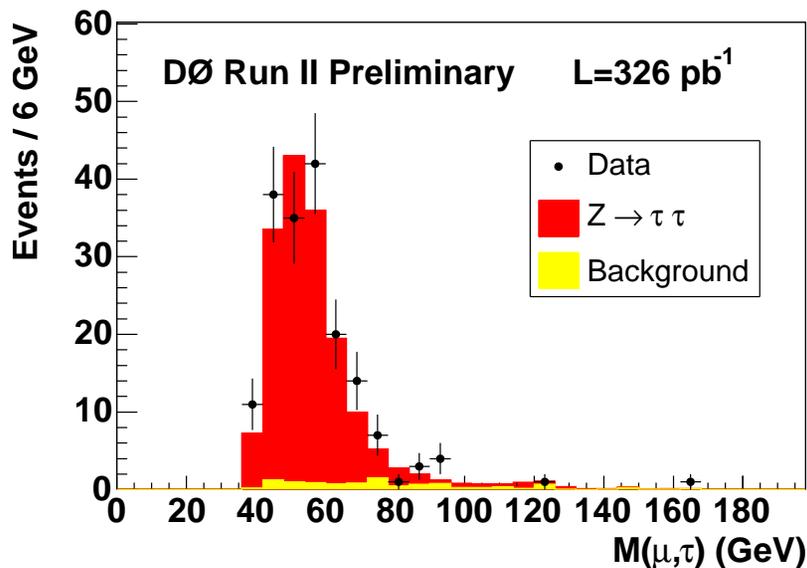
→ multiple  $\tau$  leptons in final state

65% of  $\tau$  leptons decay hadronically

- reconstructed as 1 or 3 tracks pointing to narrow energy deposition in calorimeter
- using neural networks to separate  $\tau$ -decays from jets



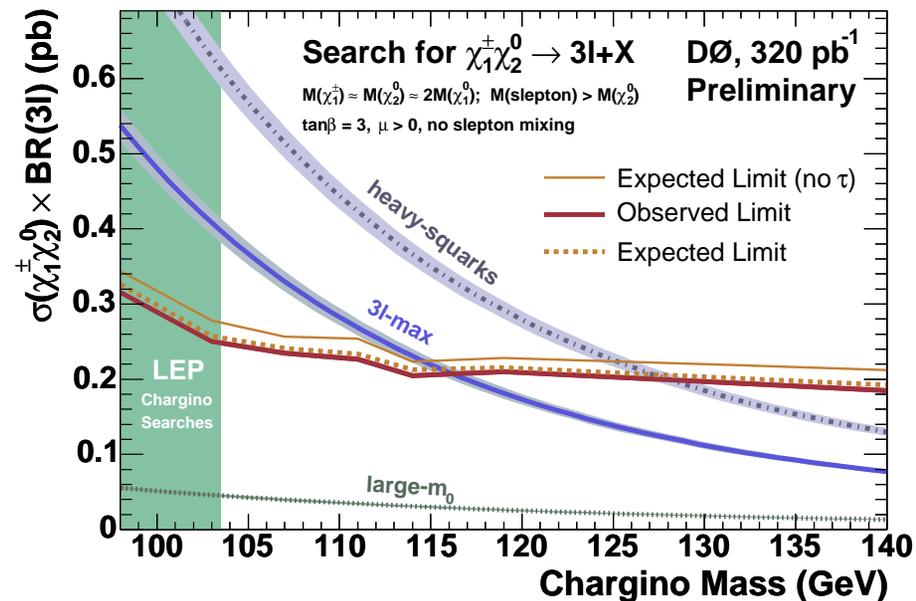
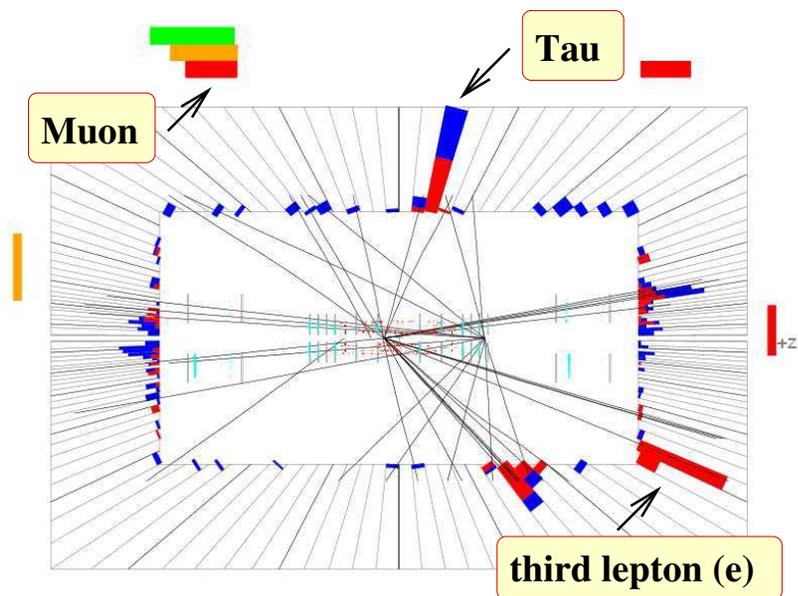
Reference signal:  $Z \rightarrow \tau\tau \rightarrow e/\mu + \text{hadrons}$



# Search for Charginos and Neutralinos

Two new  $D\bar{0}$  trilepton analyses:  $e/\mu + \tau +$  isolated track

Selection	Expected Background	Observed	Signal ( $m_{\tilde{\chi}^\pm} = 110$ GeV)
$e e \ell$	$0.21 \pm 0.12$	0	$1.9 \pm 0.2$
$e \mu \ell$	$0.31 \pm 0.13$	0	$1.6 \pm 0.1$
$\mu \mu \ell$	$1.75 \pm 0.57$	2	$1.3 \pm 0.2$
ls- $\mu \mu$	$0.66 \pm 0.37$	1	$0.7 \pm 0.1$
$e \tau \ell$	$0.58 \pm 0.14$	0	$0.4 \pm 0.1$
$\mu \tau \ell$	$0.36 \pm 0.13$	1	$0.7 \pm 0.1$
<b>Combined</b>	<b><math>3.87 \pm 0.81</math></b>	<b>4</b>	<b><math>6.6 \pm 0.3</math></b>



Interpretation of results in models with light stau (high  $\tan\beta$ ) still in progress

# Search for Supersymmetry: R-Parity Violation

Most general Superpotential contains 45 Yukawa terms leading to violation of Lepton/Baryon-Number:

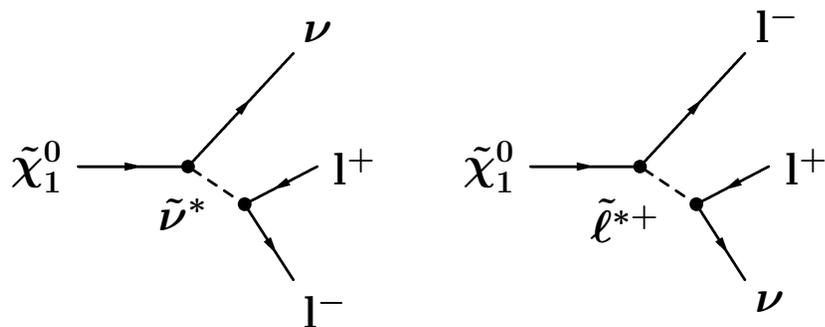
$$W = W_{RPC} + W_{RPV}$$

$$W_{RPV} = \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

- couplings are constrained by searches for L- and B-violation, but could be non-zero
- all terms violate conservation of multiplicative quantum number R-parity
- need to study SUSY with and without conservation of R-Parity

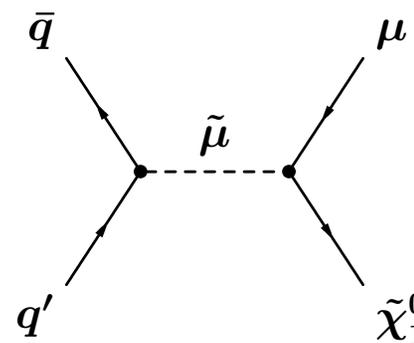
Important consequences of R-parity violation for SUSY collider signatures:

LSP can decay into SM fermions:



(For non-zero  $L_i L_j \bar{E}_k$ -coupling)

Resonant production of SUSY particles:



(For non-zero  $L_i Q_j \bar{D}_k$ -coupling)

$\emptyset$  search channels:

$$\tilde{\chi}^\pm \tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 + X \rightarrow 4\ell + E_T + X$$

$$\tilde{\mu} \rightarrow \mu + \tilde{\chi}_1^0 \rightarrow 2\mu + 2j$$

# Search for Charginos and Neutralinos: RPV

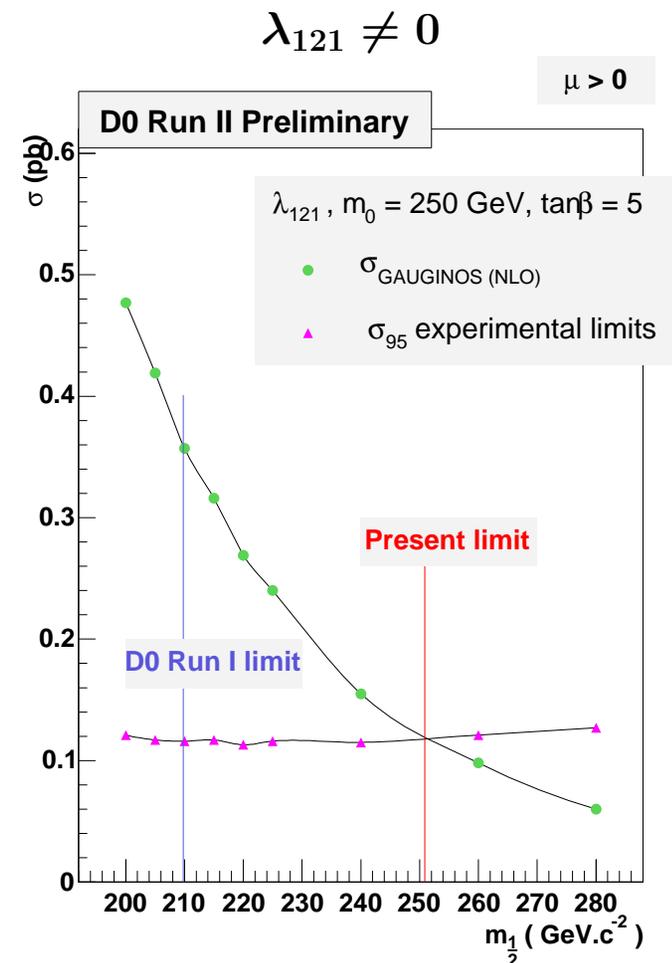
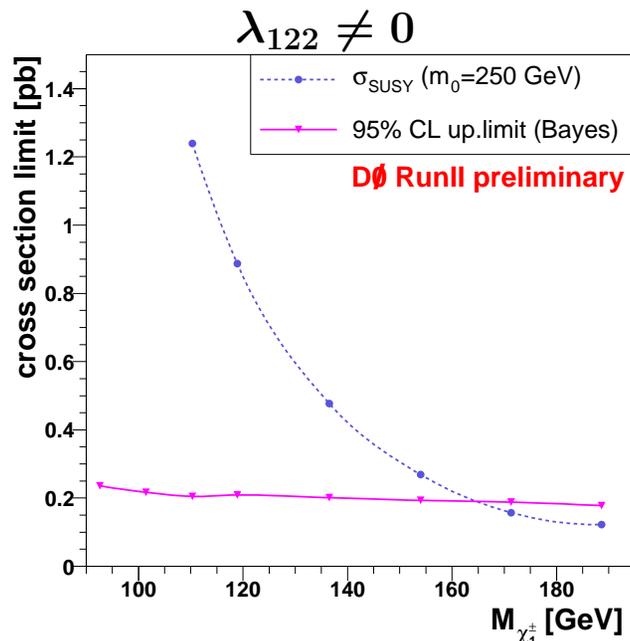
Analyzed up to  $240 \text{ pb}^{-1}$  with 5 dedicated trilepton selections:

- requiring 3 (out of 4) identified leptons
- very low pt cuts on third lepton (down to 3 GeV)
- loose  $E_T$  requirement

Backgrounds dominated by DY with fake 3rd lepton, WW/WZ:

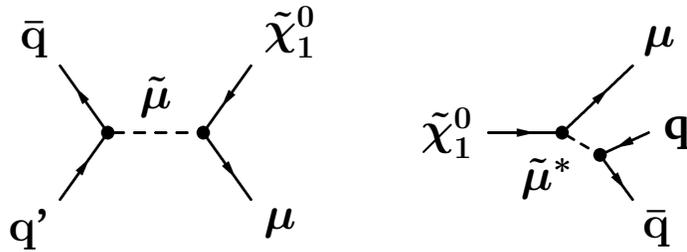
Selection	Background	Observed
$\mu\mu\mu, e\mu\mu$	$0.6 \pm 1.4$	2
$ee\mu, eee$	$0.5 \pm 0.4$	0
$ee\tau$	$1.0 \pm 1.4$	0

Interpretation within two reference scenarios:



# Search for Supersymmetry: RPV

## Search for resonant smuon production ( $154 \text{ pb}^{-1}$ ):



- Two muons with  $p_T > 8$  and  $p_T > 20$  GeV
- Two jets with  $p_T > 15$  GeV
- Topological cuts to reduce Z+jets background
- Reconstruction of Neutralino and Smuon invariant masses

## Background Expectation:

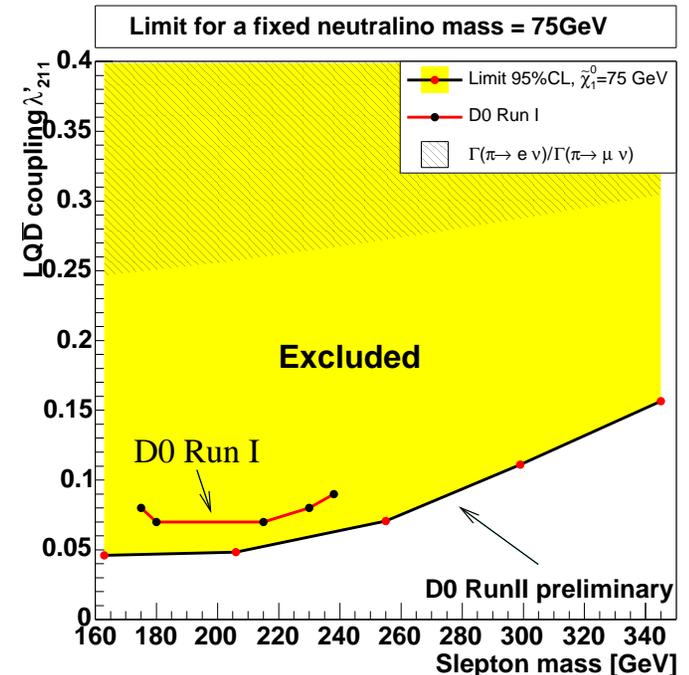
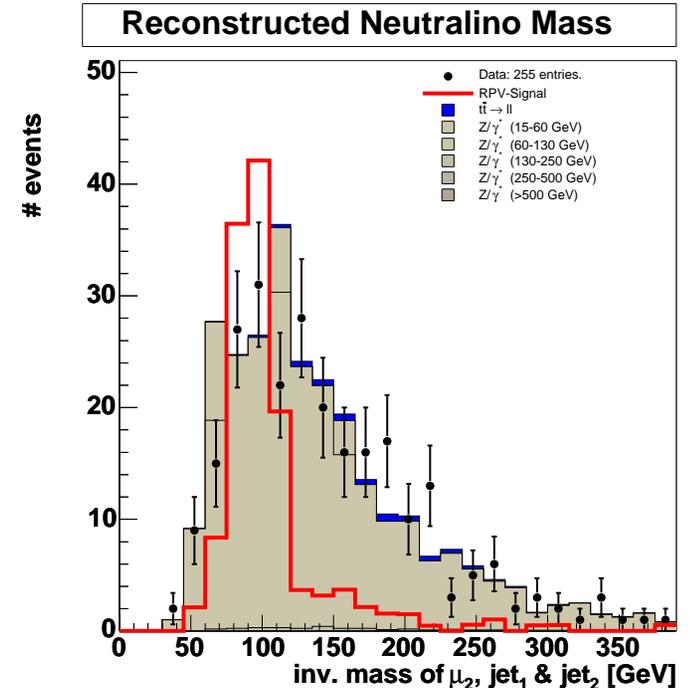
- between 0.1 and 1.6 events (depending on mass hypothesis)

## No excess observed in data:

- two or less events for all masses

## Interpretation:

- limits on  $\lambda'_{211}$  as a function of Smuon and Neutralino mass



# Search for Stable Charginos

Charginos with small mass difference to LSP can be quasi-stable (Anomaly-mediated SB)

→ slow-moving massive stable charged particle

Experimental signature: two high-pt muons with out-of-time scintillator hits

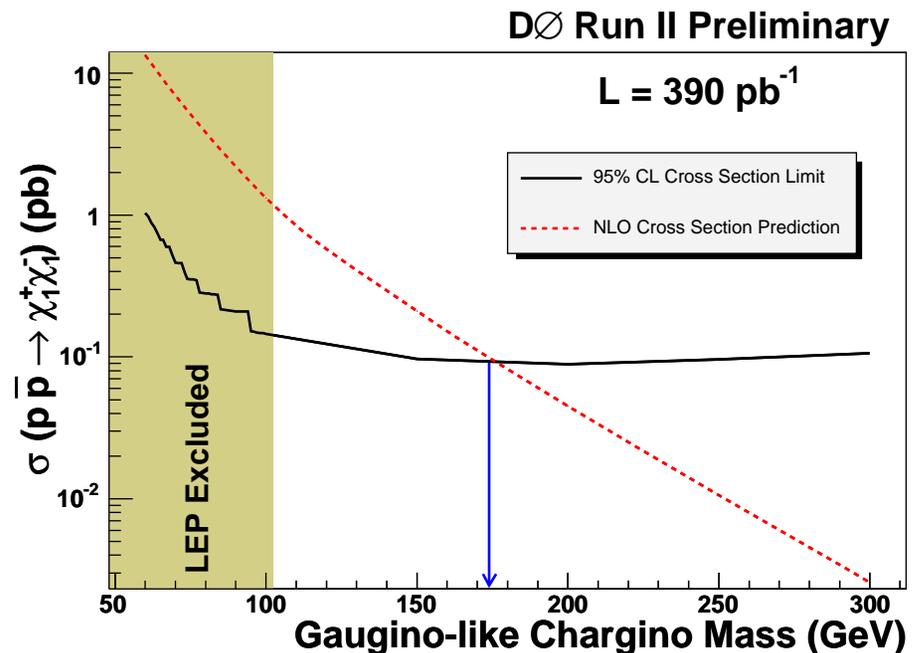
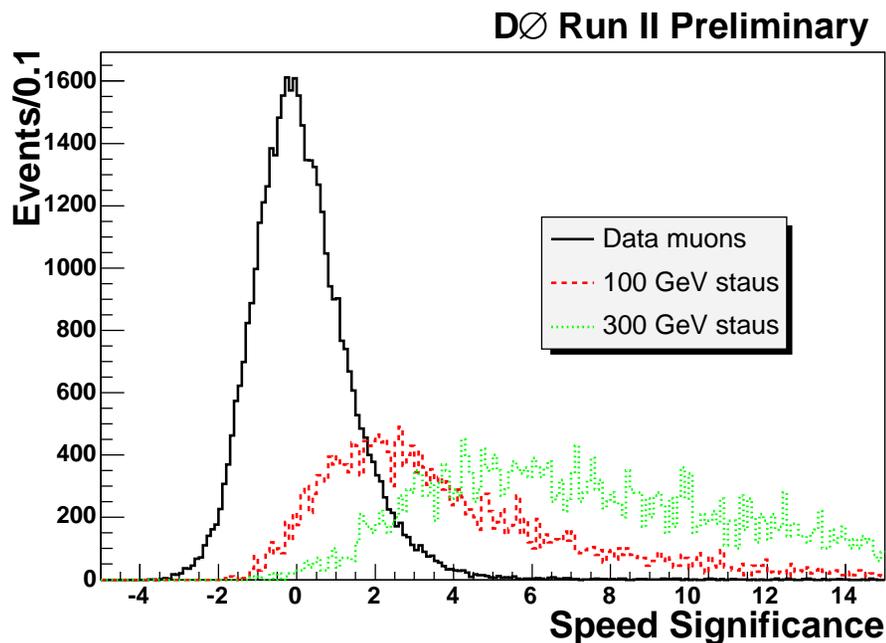
Additional Handle: large  $dE/dx$  in tracker and calorimeter (not used by current analysis)

Analysis of  $390 \text{ pb}^{-1}$  of data collected with dimuon trigger:

- require speed of muons to be significantly below  $c$
- kinematic cuts against  $Z \rightarrow \mu\mu$  with poorly measured timing

Results ( $m > 100 \text{ GeV}$ ): no events observed,  $0.66 \pm 0.06$  events expected

→ new chargino mass limits: 140 GeV (higgsino-like), 174 GeV (gaugino-like)



# Search for Supersymmetry with Gravitino LSP

Gauge Mediated SUSY Breaking: Gravitino  $\tilde{G}$  is LSP

Assuming Neutralino NLSP:  $\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}$

→ Chargino/Neutralino production leads to final states containing  $\gamma\gamma + \cancel{E}_T$

→ Inclusive search for 2 photons plus  $\cancel{E}_T$  ( $263 \text{ pb}^{-1}$ )

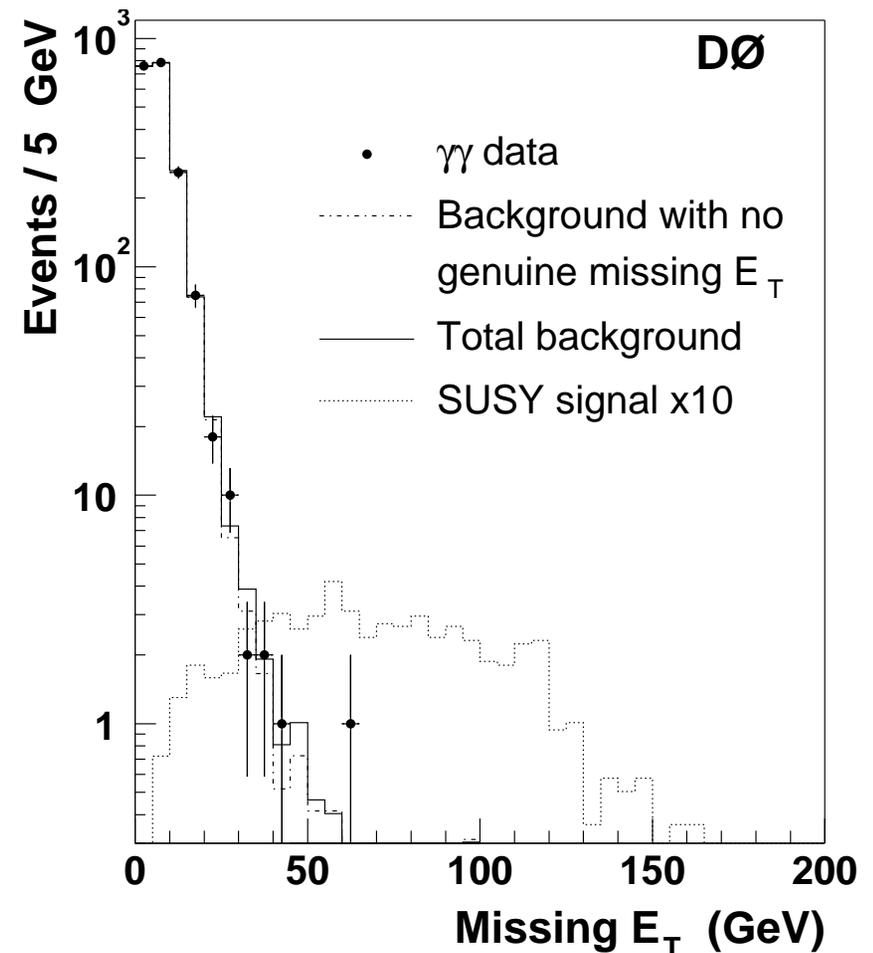
## Main backgrounds

- $jj$ ,  $\gamma j$  and  $\gamma\gamma$  production with fake  $\cancel{E}_T$
- $W\gamma$  with  $W \rightarrow e\nu$  and fake photon
- all modelled from data

Optimized Cut:  $\cancel{E}_T > 40 \text{ GeV}$

→ 2 events observed in data

→  $3.7 \pm 0.6$  expected from fakes



# Search for Supersymmetry with Gravitino LSP

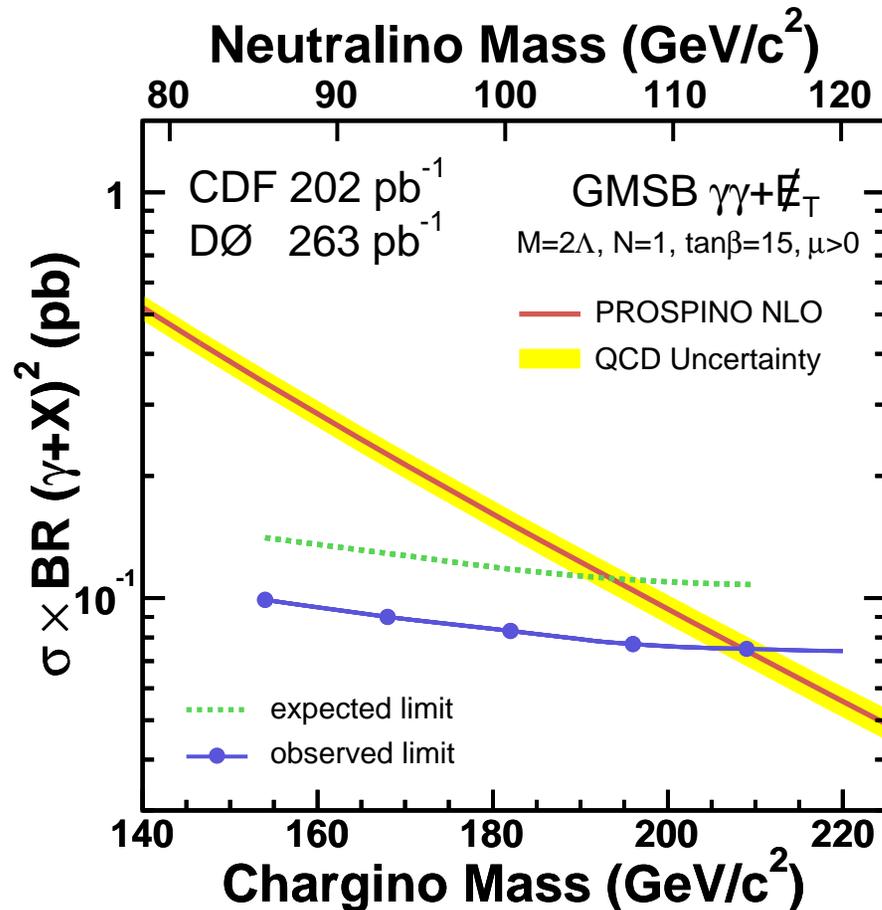
Mass limits on Chargino and Neutralino ( $N_5=1$ ,  $M_m=2\Lambda$ ,  $\tan\beta=15$ ,  $\mu > 0$ ):

DØ (263 pb<sup>-1</sup>):  $m_{\tilde{\chi}_1^0} > 108$  GeV,  $m_{\tilde{\chi}^\pm} > 195$  GeV

CDF (202 pb<sup>-1</sup>):  $m_{\tilde{\chi}_1^0} > 93$  GeV,  $m_{\tilde{\chi}^\pm} > 168$  GeV

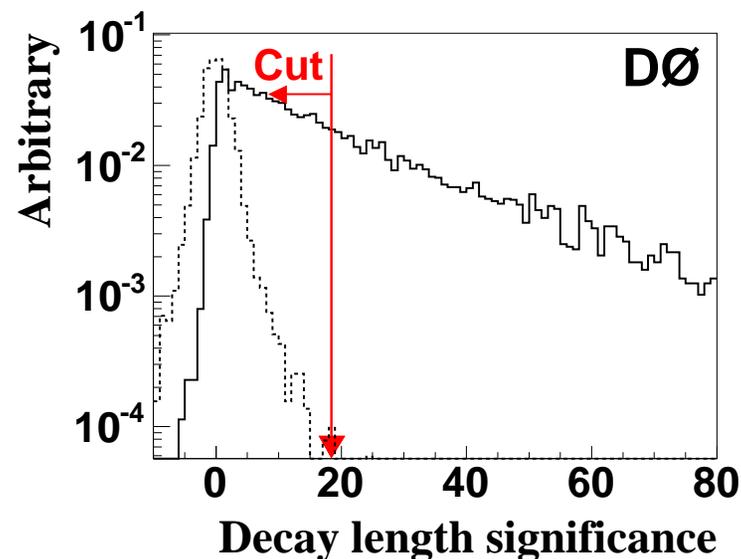
Tevatron New Phenomena Working Group: first combined Run II result

TEVNPWG:  $m_{\tilde{\chi}_1^0} > 114$  GeV,  $m_{\tilde{\chi}^\pm} > 209$  GeV



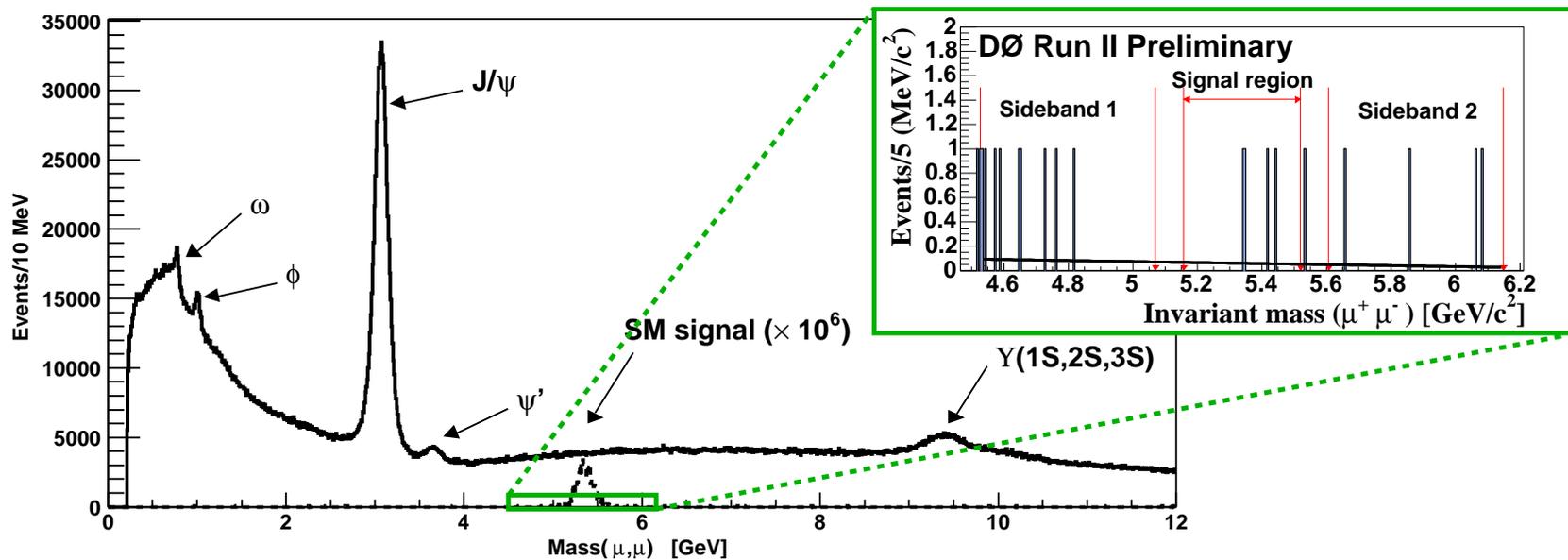
# Search for Supersymmetry: $B_s \rightarrow \mu^+ \mu^-$

- SM prediction:  $BR(B_s \rightarrow \mu^+ \mu^-) = 3.8 \times 10^{-9}$
- can be enhanced by non-SM graphs:
  - SUGRA:  $\sim (\tan\beta)^6$
  - significant at high  $\tan\beta$ :  $BR = O(10^{-7})$
  - complementary to trilepton search
- Tevatron: large production rate for  $B_s$
- Selection: two isolated muons, displaced vertex
- Results (limits at 95% C.L.):



DØ ( $300 \text{ pb}^{-1}$ ):  $4.3 \pm 1.2$  expected, 4 observed →  $BR(B_s \rightarrow \mu^+ \mu^-) < 3.7 \times 10^{-7}$

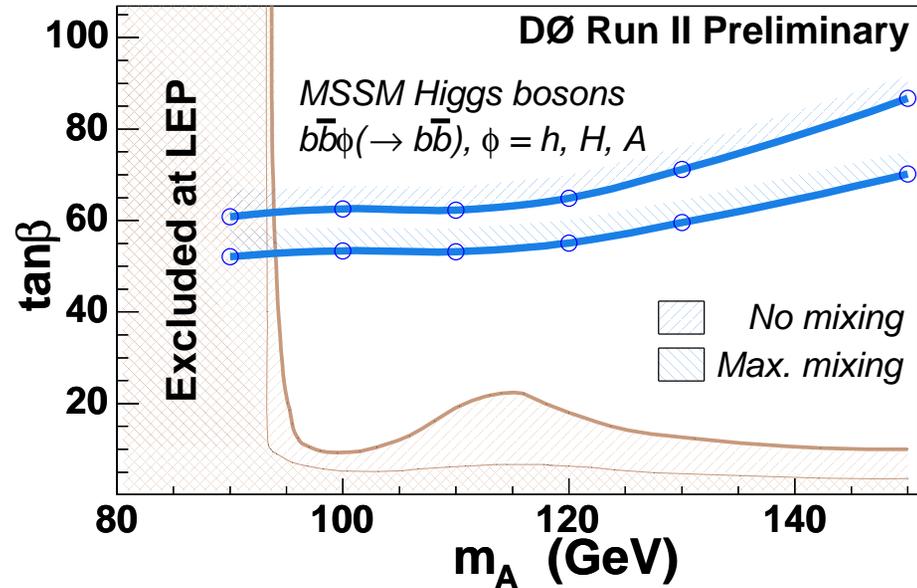
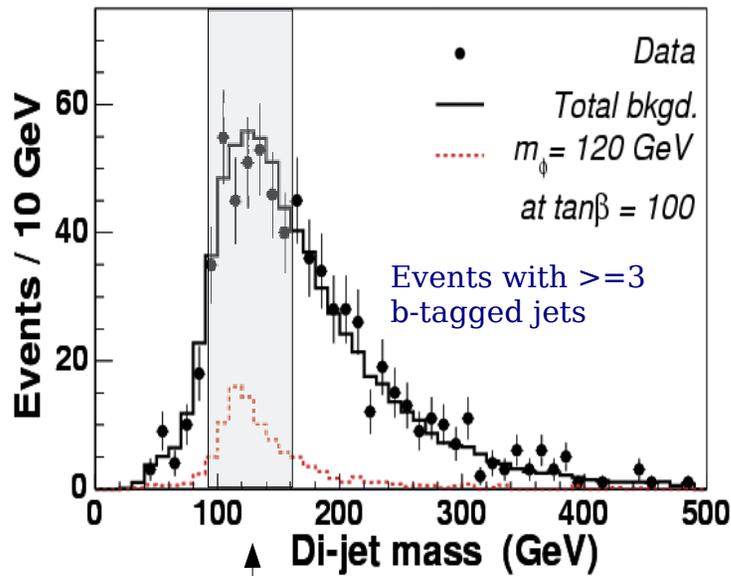
CDF ( $364 \text{ pb}^{-1}$ ):  $1.5 \pm 0.2$  expected, 0 observed →  $BR(B_s \rightarrow \mu^+ \mu^-) < 2.0 \times 10^{-7}$



# Search for SUSY Higgs: $hb(\bar{b}) \rightarrow b\bar{b}b(\bar{b})$

SUSY:  $hb\bar{b}$ -coupling enhanced at large  $\tan\beta \rightarrow$  large cross-sections for  $hb(\bar{b})$  production

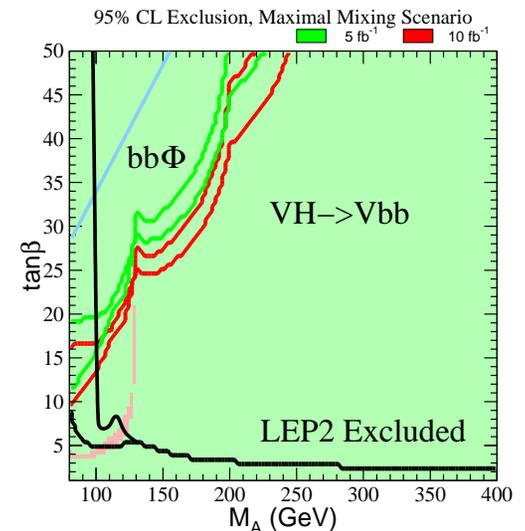
- Selection: at least 3 b-jets
- Backgrounds: multijet production (modelled using data, cross-checked with MC)
- Reconstruction of Higgs boson mass in  $b\bar{b}$  spectrum



- still no hint for a signal
- $\rightarrow$  significantly improved limits on  $\tan\beta$  as a function of  $m_A$

## Reminder:

- SUSY predicts at least one Higgs boson with  $m \leq 135 \text{ GeV}$
- combination of  $b\bar{b}h$  and VH analyses should allow a test at 95% C.L. with  $5\text{fb}^{-1}$  (mhmax scenario)



# Conclusions and Outlook

- DØ SUSY searches are exploring new territory beyond existing limits
- No evidence for any SUSY signal yet
- New Squark/Gluino mass limits up to 340 GeV
- Chargino/Neutralino search in trileptons has reached sensitivity beyond LEP
- Considering large variety of SUSY models:
  - with and without R-parity violation
  - gravity/gauge/anomaly-mediated SUSY breaking
  - current limits on chargino mass up to 210 GeV
- Powerful complementary tests for SUSY via rare decays and Higgs searches
- Future prospects are good – second-generation analyses have started:

- will include new channels
- continuously improving reconstruction techniques
- much larger dataset:  $1 \text{ fb}^{-1}$  by Fall!

